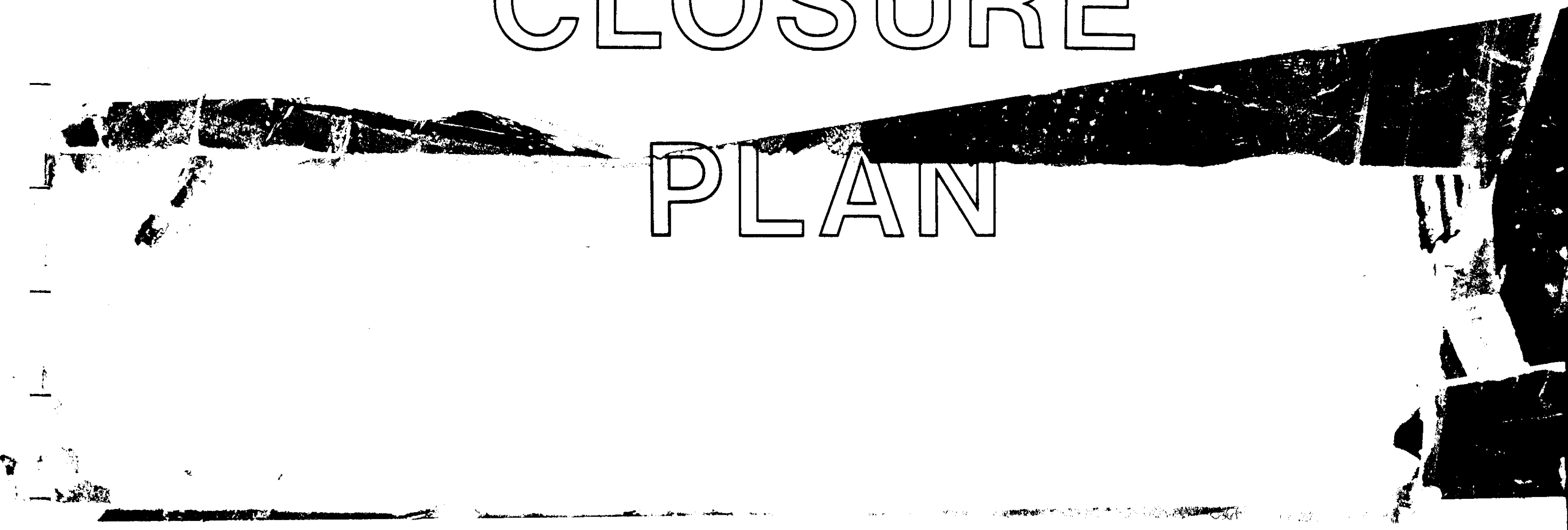
012554

ISLAND COPPER MINE

CLOSURE PLAN



Prepared by:

BHP-UTAH
Minerals International

Island Copper Mine
Port Hardy, British Columbia

September 1990

EXECUTIVE
SUMMARY

EXECUTIVE SUMMARY

BHP-UTAH Mines Ltd. has developed a reclamation strategy designed to return disturbed areas to productive land forms, useful for wildlife habitat, recreation and forestry. The overall objective is that the site be self-maintaining after equilibrium has been achieved and the integrity of the environment assured.

Reclamation has been ongoing over the life of the mine. Of the 732.6 ha which had been disturbed to December 1989, 214.9 ha are contained in the open pit which will be flooded. This leaves a disturbed area of approximately 518 ha. At present 103 ha have been reclaimed, representing 20% of land disturbed. Plate 1 is an overall air photo of the Island Copper Mine and Plate 2 is an example of one of the land dumps that have been recontoured and vegetated. Returning disturbed areas to productive habitat has been done successfully at Island Copper and the mine has received several Provincial Awards for its efforts.

The outstanding issues to be considered on closure of the Island Copper operation include the quality of the drainages from the dumps, the habitat created by the flooding of the pit and the long term stability of dumps and pit walls.

Extensive work has been carried out over the past three years to evaluate the nature of dumps at Island Copper and to determine the long term water quality of their drainages. Individual drainages from several dumps currently exhibit low pH and elevated levels of dissolved zinc, copper and manganese. Combined drainages from the land dumps exhibit alkalinity ranging from 50 to 130 mg/l as $CaCO_3$, depending on the season sampled. These drainages meet the British Columbia Pollution Control Objectives for the mining industry except in the autumn wet season each year. Strategies to mitigate acid drainage are currently being developed.

A model has been developed for flooding of the open pit with seawater. The results indicate that an anoxic lower layer will develop below the 100 meter depth in the pit and an oxygenated upper layer with dissolved oxygen greater than 5 mg/l will develop in the surface 25 metres. The channel connecting the pit with Rupert Inlet will be navigable by small vessels. Flooding the pit will mitigate, to some extent, habitat losses resulting from the partial filling of Rupert Inlet by the beach dump.

PLATE 1 ISLAND COPPER MINE, RUPERT INLET B.C. (JULY 1990)

PLATE 2 NORTH DUMP 1990

(Recontoured 1978, Seeded and Planted 1980)

A plan for increasing fish habitat in Rupert Inlet has been developed through discussions with the Federal Department of Fisheries and Oceans. Beach cusps (embayments) will be created along the beach face which will increase the surface area of the productive near shore habitat.

TABLE OF CONTENTS

EXECUTIVE SUMMARY i

TABLE OF CONTENTS v

LIST OF TABLES viii

LIST OF FIGURES ix

LIST OF PLATES x

1.0 INTRODUCTION 1-1
- 1.1 Background 1-1
- 1.2 Objective 1-1
- 1.3 Island Copper History 1-2
- 1.4 South Wall Pushback 1-2

2.0 ENVIRONMENTAL SETTING 2-1
- 2.1 Climate 2-1
- 2.2 Landforms and Geology 2-2
  - 2.2.1 Landforms 2-2
  - 2.2.2 Geology 2-2
- 2.3 Hydrology 2-4
- 2.4 Vegetation 2-4
- 2.5 Wildlife 2-4

3.0 RECLAMATION 3-1
- 3.1 Introduction 3-1
- 3.2 Reclamation Strategy 3-1
- 3.3 Reclamation Plan 3-1
  - 3.3.1 Land Dumps 3-1
  - 3.3.2 Beach Dump 3-2
  - 3.3.3 Open Pit 3-2

3.3.3.1 Pit Flooding 3-2
3.3.3.2 Pit Walls Above Sea Level 3-27
3.3.4 Mill Tailings 3-28

4.0 WATER MANAGEMENT FOR CLOSURE 4-1

4.1 Introduction 4-1

4.2 Acid Drainage Characterization 4-1

4.3 Drainage Control 4-5
4.3.1 Hydrology of Land Dumps 4-5

4.4 Closure Treatment of Acid Drainage 4-14
4.4.1 Passive Treatment 4-14
4.4.2 Active Chemical Treatment 4-14
4.4.3 Passive In-Pit Treatment 4-15
4.4.4 Control of Acid Drainage 4-15

5.0 DUMP EVALUATION 5-1

5.1 Rock Dumps 5-1
5.1.1 Introduction 5-1

5.2 Land Dumps 5-1
5.2.1 North Dump 5-2
5.2.1.1 The Caps 5-3
5.2.1.2 The Eastern Most Outslope (EMO) 5-3
5.2.1.3 The Old North Dump 5-3
5.2.1.4 North Dump Drilling Program 5-3
5.2.1.5 North Dump Summary 5-10
5.2.2 West Dump 5-10
5.2.3 South Dump 5-10
5.2.4 Northwest Dump 5-10

5.3 Marine Dump 5-11
5.3.1 Marine Dump Hydrology 5-12
5.3.2 Marine Dump Water Quality 5-12

APPENDICES

Appendix 1: Pit Model A-1

Appendix 2: Northwest Dump Study B-1

Appendix 3: Beach Dump Water Quality C-1

LIST OF TABLES

2-1 Meteorological Summary, Port Hardy (Normal) Environment Canada 2-1

3-1 Parameter Settings for Pit Model Simulations 3-5

3-2 Pit Wall Acid Potential Test Results 3-29

3-3 Island Copper Post-Discharge Monitoring of Tailings 3-33

4-1 Water Quality Old End Creek (Ground Water Seep) RTC 1989 4-2

4-2 Water Quality North Diversion Ditch (NDD) 1989 4-3

4-3 Water Quality Eastern Most Outslope (EMO) 1989 4-4

4-4 East Drainage Ditch (EDD) Flows 4-6

4-5 Ten-Eight Ditch (TED) Flows 4-8

4-6 Old Trey Creek (TRC) Flows 4-10

5-1 North Dump Development 1971 - 1985 Waste Rock and Till 5-2

5-2 North Dump Composition 5-5

5-3 Drilling Information for Holes on North Dump, April and May 1988 5-5

5-4 Acid-Base Accounting Results for Samples from Drilling Program on North Dump at ICM 5-7

5-5 Beach Hole Summary Data 5-14

5-6 Dissolved Metals in Seawater Off Beach Dump 5-16

5-7 24-Hour Time Study of Dissolved Zinc off Beach Dump 5-16

5-8 Dissolved Metals in Seawater MID Rupert Inlet near Mine Site (STN' A) 1977 - 1989 5-18

LIST OF FIGURES

1-1 Location Map 1-3

2-1 Mine Site Water Sheds and Dump Boundaries 2-3

3-0 Flooded Open Pit, Channel and Beach Dump Shoreline, 1998 3-3

3-1 Annual Vertical Profiles (top) and Depth-Time Surface (bottom) of Dissolved Oxygen from Simulation 1 3-6

3-2 Annual Vertical Profiles (top) and Depth-Time Surface (bottom) of Dissolved Oxygen from Simulation 2 3-7

3-3 Annual Vertical Profiles (top) and Depth-Time Surface (bottom) of Dissolved Oxygen from Simulation 3 3-8

3-4 Annual Vertical Profiles (top) and Depth-Time Surface (bottom) of Dissolved Oxygen from Simulation 4 3-9

3-5 Annual Vertical Profiles (top) and Depth-Time Surface (bottom) of Dissolved Oxygen from Simulation 5 3-10

3-6 Annual Vertical Profiles (top) and Depth-Time Surface (bottom) of Dissolved Oxygen from Simulation 6 3-11

3-7 Annual Vertical Profiles (top) and Depth-Time Surface (bottom) of Dissolved Oxygen from Simulation 7 3-12

3-8 Time Series Dissolved Oxygen Concentration at 4.0 m. Intervals from Simulation 8 3-14

3-9 Time Series Dissolved Oxygen Concentration at 4.0 m. Intervals from Simulation 9 3-15

3-10 Time Series Dissolved Oxygen Concentration at 4.0 m. Intervals from Simulation 10 3-16

3-11 Time Series Dissolved Oxygen Concentration at 4.0 m. Intervals from Simulation 11 3-17

3-12 Time Series Dissolved Oxygen Concentration at 4.0 m. Intervals from Simulation 12 3-18

LIST OF FIGURES (cont'd)

3-13 Time Series Dissolved Oxygen Concentration at 4.0 m. Intervals from Simulation 13 3-19

3-14 Time Series Dissolved Oxygen Concentration at 4.0 m. Intervals from Simulation 14 3-20

3-15 Time Series Dissolved Oxygen Concentration at 4.0 m. Intervals from Simulation 15 3-21

3-16 Time Series Dissolved Oxygen Concentration at 4.0 m. Intervals from Simulation 16 3-22

3-17 Time Series Dissolved Oxygen Concentration at 4.0 m. Intervals from Simulation 17 3-23

3-18 Net Neutralization Potential of Pit Wall Above Sea Level 3-32

4-1 East Drainage Ditch Flows (Sept 1989-Aug 1990) 4-12

4-2 Ten-eighty Ditch Hydro Graph (Oct 1989-Aug 1990) 4-13

5-1 Dump and Drill Hole Locations 5-4

5-2 Net Neutralizing Potential of North Dump Drill Holes 5-9

5-3 Beach Dump Wells 5-13

5-4 Dissolved Zinc in Seawater and Tide Height During 24-hr Time Study 5-17

LIST OF PLATES

Plate 1 Island Copper Mine, Rupert Inlet, B.C. ii

Plate 2 North Dump 1990 iii

1. INTRODUCTION

1 - Introduction

1.0 INTRODUCTION

1.1 Background

On January 28, 1981, BHP-UTAH Mines Ltd. was issued reclamation permit M-9. The permit has four major provisions as follows:

(a) All disturbances are to be reclaimed to the satisfaction of the Chief Inspector of Mines.

(b) Plans for the final pit and lake design are to be submitted to the Chief Inspector and reviewed by the Advisory Committee on Reclamation.

(c) Plans and programs approved by the Chief Inspector shall become part of the permit.

(d) New developments and their accompanying reclamation programs require the approval of the Chief Inspector pursuant to the *Mining Regulations Act*.

BHP-UTAH Mines Ltd. has developed a reclamation strategy that was designed to return disturbed areas to productive land forms, useful for wildlife habitat, recreation and forestry. The mine code requires that the land surface be reclaimed to an acceptable use that considers previous and potential use.

BHP-UTAH Mines Ltd. interprets this to mean that a multiple use strategy is required for reclaimed land. This is consistent with the mine's stated land use objectives. It is assumed that disturbances are reclaimed to the Chief Inspector's satisfaction when the land use objectives are met.

1.2 Objective

As a result of the amendment to Island Copper's mine plan associated with the South Wall Pushback (BHP-UTAH, 1988), BHP-UTAH Mines Ltd. committed to the development of a closure plan for the property. This report is presented as a fulfillment of that commitment.

1.3 Island Copper History

The Island Copper Mine, operated by BHP-UTAH Mines Ltd., is located on the north shore of Rupert Inlet, about 16 kilometres south of Port Hardy on the north end of Vancouver Island (Figure 1-1).

In January, 1966, BHP-UTAH Mines Ltd. optioned a group of claims and subsequent exploration resulted in the delineation of the Island Copper ore body by May 1969. Construction of the mine began in June 1969 and the first concentrates were produced in September 1971. The mine has been in continuous production since 1971 and was originally planned for closure in 1992. The South Wall Pushback Project has resulted in a mine life extension of approximately four years. Closure is now projected to be late 1996 unless further ore reserves are delineated during the intervening period.

1.4 South Wall Pushback

As part of the permitting process for the South Wall Pushback, BHP-UTAH Mines Ltd. submitted a report to the Vancouver Island Regional Reclamation Advisory Committee containing its reclamation plan and committed to submit a closure plan in 1990. The South Wall Pushback barrier wall has been successfully constructed and mining has commenced.

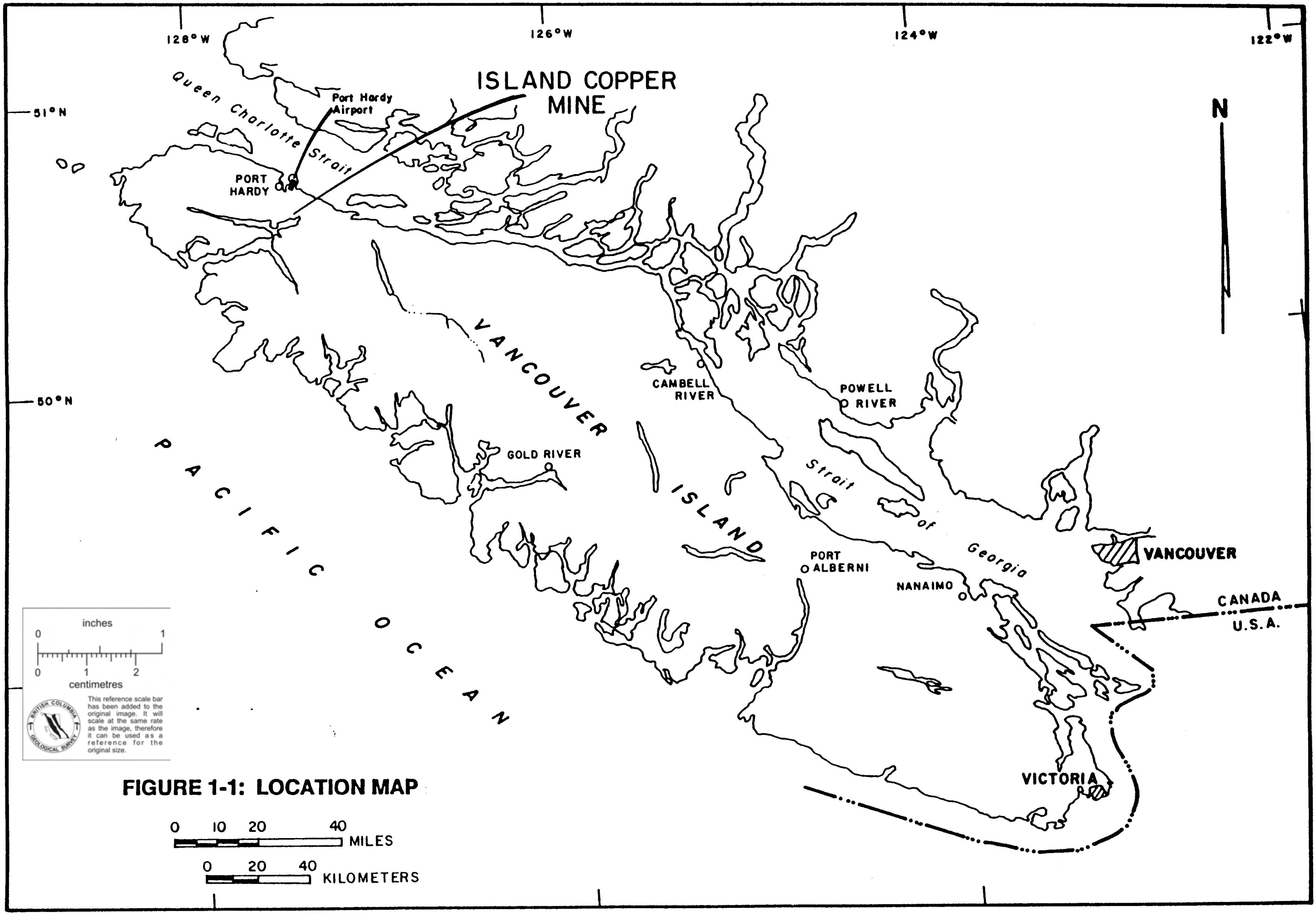


FIGURE 1-1: LOCATION MAP

2. ENVIRONMENTAL SETTING

2 - Environmental Setting

2.0 ENVIRONMENTAL SETTING

2.1 Climate

The Island Copper mine is located on the north end of Vancouver Island and experiences mild humid coastal weather, all year long. Table 2-1 presents the normal temperature and rainfall for the area.

Table 2-1

Meteorological Summary
Port Hardy (Normal) Environment Canada

	Temperature Monthly Mean °C		Precipitation		
			Rain (mm)	Snow (cm)	Total (mm)
January	2.4		181.6	29.6	211.3
February	3.9		148.3	10.5	159.3
March	4.4		128.5	11.0	141.8
April	6.6		106.2	1.3	107.5
May	9.3		68.2	TR	68.6
June	11.8		70.7		70.7
July	13.6		52.0		52.0
August	13.8		69.0		69.0
September	11.8		136.2		136.2
October	8.7		244.6	.2	244.8
November	5.3		239.8	4.0	244.7
December	3.5		260.3	15.5	276.9
Annual Mean	8.0	Total	1705.8	72.1	1782.8

Significant precipitation occurs in all but the summer months of May through August. Most precipitation (i.e. 96%) falls as rain. There is minimal snow accumulation and significant runoff in local streams is associated with rain storm events.

2.2 Landforms and Geology

2.2.1 Landforms

Northernmost Vancouver Island is a region of generally subdued hummocky local topography densely treed by a coniferous West Coast Rain Forest (Johnson, 1974). Elevations rise to approximately 610 metres both north and south of the mine.

Rupert Inlet occupies an over-deepened middle section of a glacially scoured topographic trough that extends easterly across Vancouver Island. The mine site is located on a south facing slope with the site elevations ranging from sea level to 120 metres.

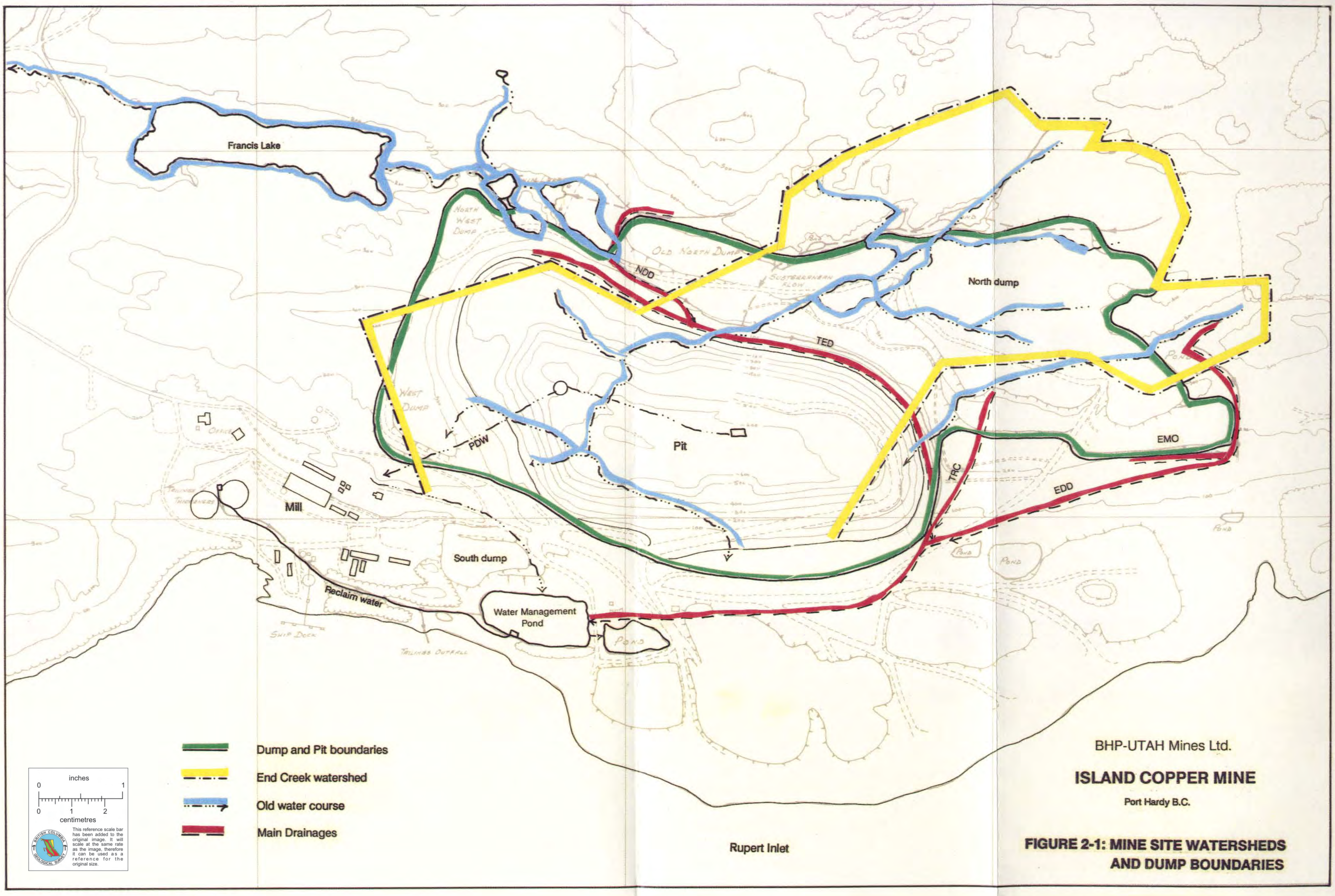
As a result of this topography, the bulk of the run-off and groundwater drainage is down slope into Rupert Inlet, controlled in the main by the now disrupted pre-mine drainage systems of the End Creek and Trey Creek watersheds (Figure 2-1). The mine drainage which does not flow southerly into Rupert Inlet flows westerly into the Stephens Creek drainage system and hence into Holberg Inlet.

2.2.2 Geology

The geology of this part of Vancouver Island is dominated by lower Triassic to lower Jurassic rocks consisting of the Karmutsen Volcanics, the Quatsino Limestone and the Bonanza Subgroup of Volcanics argillites and limestone. At the minesite a dike-like quartz-feldspar porphyry of Jurassic age intrudes the Bonanza Subgroup of Triassic Age. The ore shoots occur in Bonanza andesites pyroclastics in both the hanging wall and foot wall of the dike-like intrusive mass.

The mineralized ore shoots have been traced to a maximum depth of 425 metres below sea level and are open at depth.

The ore deposit was originally overlain by 0 to 15 metres of Quaternary deposits of glacial till, sands and gravels plus an uppermost layer of forest top soil. It is this Quaternary material that will be used as top dressing in the reclamation project. Much of these Quaternary deposits that have been stripped from the open pit since 1980 have been stockpiled for this purpose.



This reference scale bar has been added to the original image. It will scale at the same rate as the image, therefore it can be used as a reference for the original size.

BHP-UTAH Mines Ltd.

ISLAND COPPER MINE

Port Hardy B.C.

FIGURE 2-1: MINE SITE WATERSHEDS AND DUMP BOUNDARIES

2.3 Hydrology

The Island Copper open pit is situated within the original End Creek and Trey Creek watersheds (Figure 2-1). Approximately 50% of the End Creek watershed has now been mined and 30% is covered by dumps. About 15% of the Trey Creek watershed has been mined and 60% is covered by dumps. Stephen Creek is the other watershed impacted by mine activities. The northwest perimeter of the open pit touches the original Stephen Creek watershed and two small dumps are located in areas that once drained into this area. The runoff from land disturbed by mining has been directed so as to drain into Rupert Inlet via settling ponds when water quality meets Pollution Control Objectives. More detail on individual drainages is contained in Section 4.0.

2.4 Vegetation

The Island Copper Mine is located in the Coastal Western Hemlock Biogeoclimatic Zone of British Columbia. The area disturbed by mining was principally coniferous forest with associated fen, bog and marshlike habitats flanking streams, ponds, and lakes. The tree species characteristic of this zone include: western hemlock (*Tsuga heterophylla*), western red cedar (*Thuja plicata*), pacific silver fir (*Abies amabilis*), sitka spruce (*Picea sitchensis*), and Douglas fir (*Pseudotsuga menziesii*). Other species not so commonly found in the area are: western yew (*Taxus brevifolia*), lodgepole pine (*Pinus contorta*), western crabapple (*Pyrus fusca*), and red alder (*Alnus rubra*). The wetlands area supports sedges and low shrub cover (e.g. *Myrica gela* and *Spiraea douglasii*). Bog vegetation includes bur-reeds (*Sparganium* sp.), cattail (*Typha latifolia*) and *Sphagnum* sp.

2.5 Wildlife

The mine site area supports most of the wildlife species common to northern Vancouver Island. Sixty one species of birds were observed along the shoreline and in the forested areas during a survey conducted in 1976. A large flock of Canada Geese are resident on the mine site year round.

The most common small mammal is the deer-mouse; it can be found in reclaimed areas of the mine. The most common furbearer found in the area is beaver. However, mink and river otter are also observed along the intertidal areas. Raccoon have been observed around the plant site. Several large mammal species are found in the area including blacktail deer, black bear, cougar and wolf. Elk have also been observed near the mine site.

3 - Reclamation

3.0 RECLAMATION

3.1 Introduction

The Island Copper Mine has been developed as a single open pit since 1971. Until late 1989 there had been no opportunity for backfilling. The waste rock management plan has created several land dumps and one large marine dump. Eighty-four percent of the waste rock produced to date has been disposed of in the marine landfill. In this context the South Wall Pushback offers a positive feature in that additional glacial tills suitable for reclamation purposes are being mined. To date, land dumps have been recontoured to shed water and the dump faces brought to safe working slopes.

3.2 Reclamation Strategy

Disturbed land will be rehabilitated for wildlife habitat, recreation and forestry uses. The reclamation steps shall include:

- reshaping dumps for proper drainage and contouring dump faces to safe working slopes on land and to 10 degrees on the marine dump intertidal zone;
- applying a minimum of 0.5 meter of top dressing (primarily glacial till);
- seeding with an agronomic seed mixture of grasses and legumes with concomitant fertilization;
- planting Red Alder (*Alnus rubra*) and coniferous trees such as Lodgepole Pine (*Pinus contorta*).

Experience indicates that maintenance of reclaimed areas is not required to sustain growth.

3.3 Reclamation Plan

3.3.1 Land Dumps

A detailed description of the land dumps is given in Sections 4.0 and 5.0. Top dressing of dumps at Island Copper has always been part of the reclamation strategy. However, with the development of acid drainage from areas of some dumps, top dressing application techniques have been reviewed. It is concluded that a minimum of 0.5 m of till will protect shallow rooted plants from potential acid exposure. Trees and other deep rooted plants, however, could potentially come in contact with acid generating rock. Monitoring of the metal concentrations in vegetation growing on the dumps has indicated no harmful levels to date.

3.3.2 Beach Dump

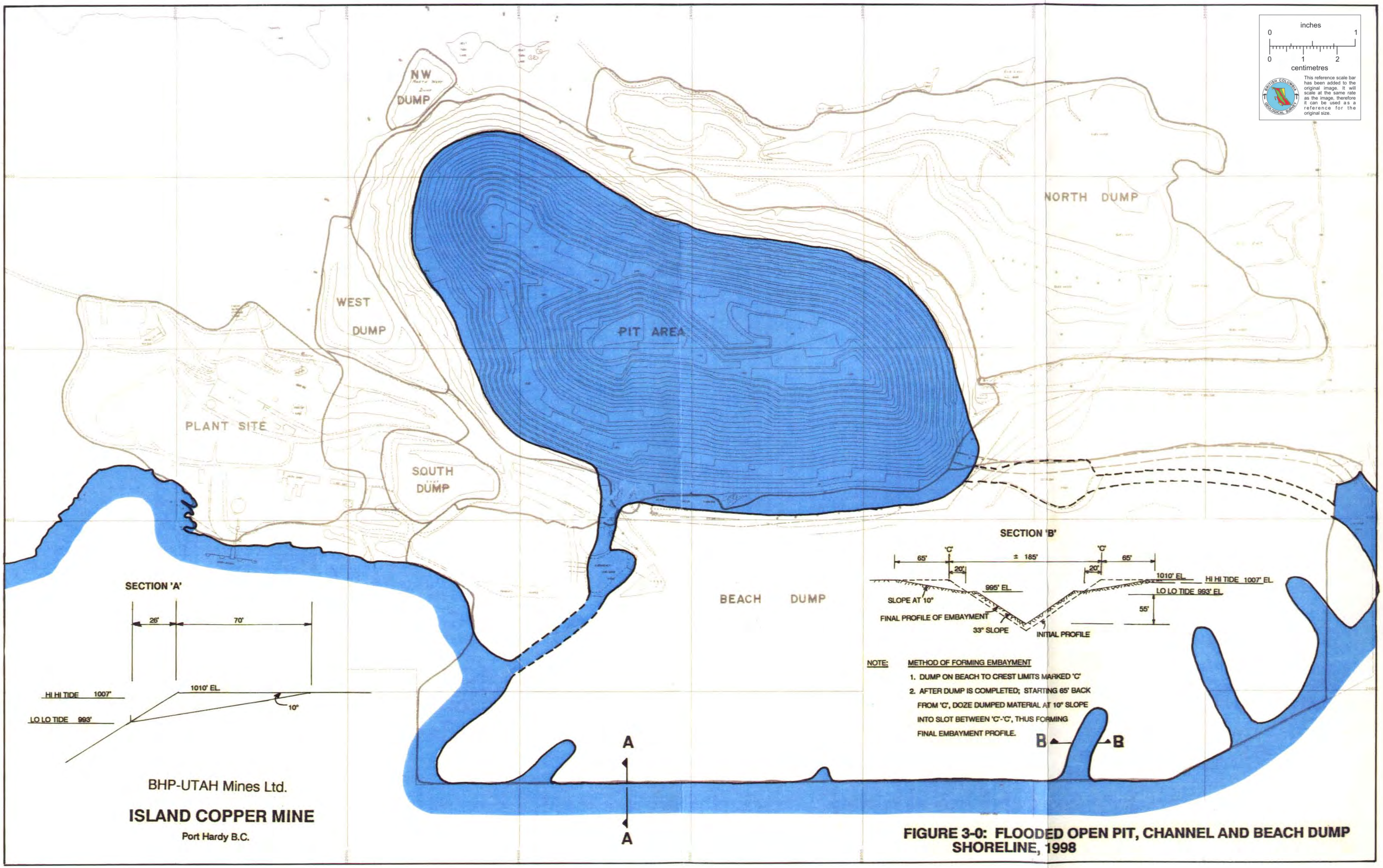
The surface of the marine dump will be treated in the same manner as the land dumps. It is estimated that reclamation will be completed within three years after the last material is deposited. The face of the dump will be resloped to 10 degrees in the intertidal zone. The shape of the shoreline (Figure 3-0) is designed to enhance marine habitat as discussed with the Department of Fisheries and Oceans. The embayments will give the dump an unique shape and provide additional shoreline fish habitat.

3.3.3 Open Pit

3.3.3.1 Pit Flooding

The development of the Island Copper mine has created a large, deep, open pit roughly elliptical in shape with a width of 1.05 km, a length of 2.35 km, and a maximum depth of 390 m. The end land use for this area has been under evaluation for many years. Potential mineral development close to the existing operation could use the pit as a disposal site for both tailings and waste rock. Current planning assumes the pit will not be used for future waste disposal and will be flooded with seawater. Flooding with seawater is preferred to freshwater for the following reasons:

- It will take 40 days to flood with seawater, but would require nearly 30 years to fill with freshwater. Some areas on the pit walls have potential to produce acidity. Rapid flooding with alkaline seawater will neutralize this.
- There would be little freshwater input into the pit on an annual basis because the catchment area is small. This would result in a deep, poorly mixed lake of likely low productivity. If flooded with seawater and permanently connected to Rupert Inlet by a channel, it will constitute a productive marine habitat. This will help mitigate habitat losses caused by the filling of Rupert Inlet by the beach dump.



NOTE: METHOD OF FORMING EMBAYMENT

1. DUMP ON BEACH TO CREST LIMITS MARKED 'C'
2. AFTER DUMP IS COMPLETED; STARTING 65' BACK FROM 'C', DOZE DUMPED MATERIAL AT 10° SLOPE INTO SLOT BETWEEN 'C'-'C', THUS FORMING FINAL EMBAYMENT PROFILE.

BHP-UTAH Mines Ltd.

ISLAND COPPER MINE

Port Hardy B.C.

FIGURE 3-0: FLOODED OPEN PIT, CHANNEL AND BEACH DUMP SHORELINE, 1998

- Acidity from the pit walls and land dumps which enters the flooded pit will be neutralized by mixing with seawater.

For these reasons the open pit will be flooded with seawater by connecting it through a shallow channel to Rupert Inlet. The goal is to produce a viable aquatic environment with the flooded pit acting as a tidal inlet.

Migration of aquatic life from Rupert Inlet into the pit is expected to occur soon after flooding is completed. It is essential that the newly created habitat have an adequate concentration of dissolved oxygen to maintain a healthy ecosystem. This in turn depends on the tidal exchange of water with Rupert Inlet through the channel combined with the vertical density structure inside the flooded pit.

To forecast the evolution of the new inlet BHP-UTAH Mines Ltd. had a consultant model the flooded pit. The detailed report is included as Appendix 1. Salient observations and conclusions are discussed below.

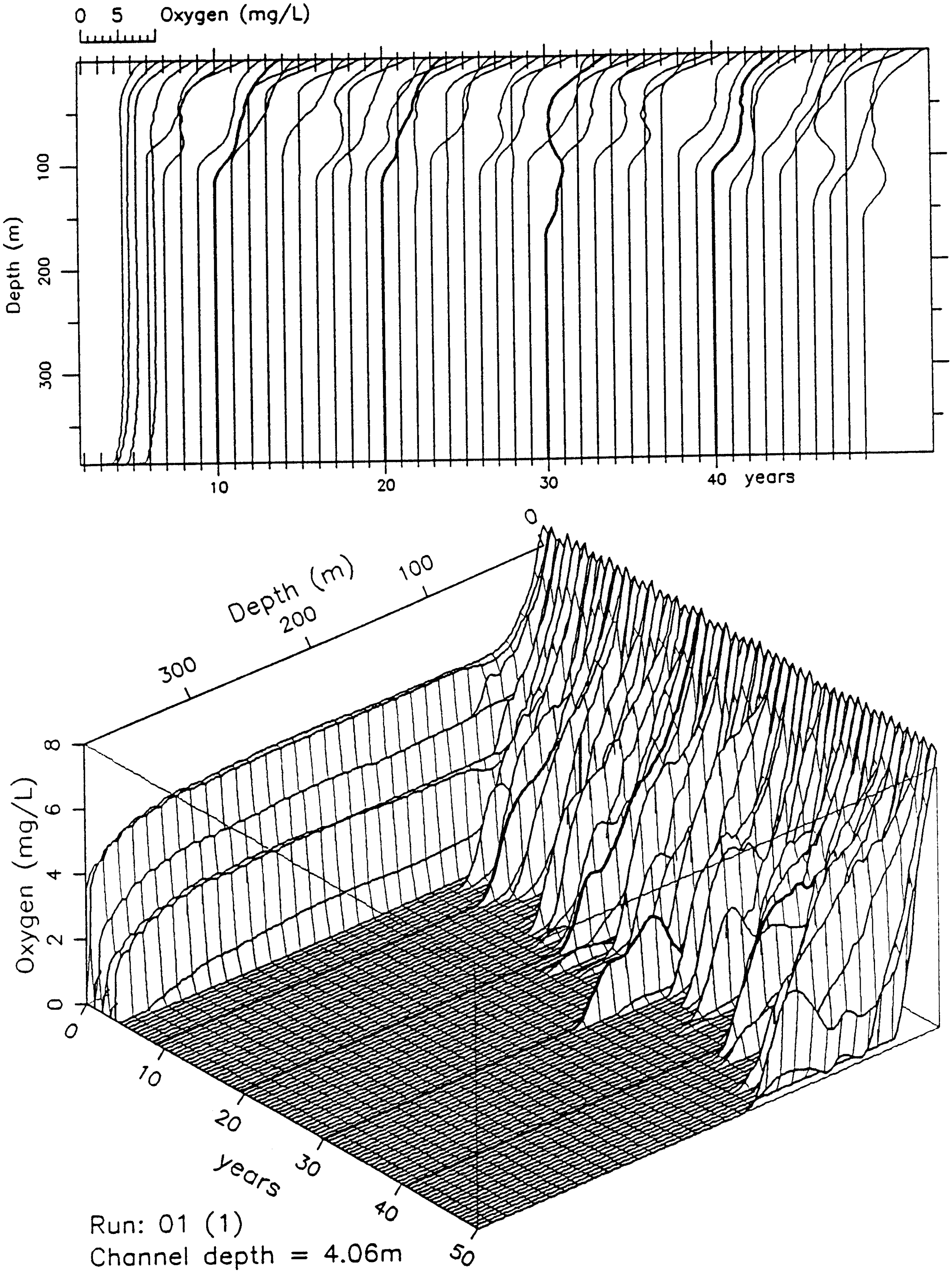
The physical oceanography of the new inlet was modelled after typical, natural inlet systems common to British Columbia. Tidal currents and density differences between the pit and Rupert Inlet waters is the main energy to create mixing and carry dissolved oxygen. The channel connecting the two water bodies will turbulently mix in-flowing water so it has similar character as the surface waters of Rupert Inlet, down to the depth of the channel. What will happen to the water once it enters the pit was modelled. Seventeen simulations were carried out using the pit model with various combinations of channel depth, oxygen demand rates, and start times. Channel depths of 4.06, 8.12, 12.18 and 16.24 m were used (1 to 4 model layers), together with several different sets of oxygen uptake rates. In addition, two start times were used: the first, on January 16, corresponds to the time of minimum density in the channel; while the second, on September 16, corresponds to the time of maximum density. Table 3-1 summarizes the parameter settings for each simulation. The duration of most runs was 50 years.

Figures 3-1 to 3-7 show the dissolved oxygen concentrations from the first seven simulations. Figures 3-1 to 3-6 correspond to runs which began at the time of minimum density in the channel, while Figure 3-7 corresponds to initial conditions at the time of maximum density. Each figure consists of an upper plot with vertical profiles of dissolved oxygen and a lower plot of the spatial and temporal distribution of dissolved oxygen. Bold lines are spaced ten years apart. Model results were saved at a rate of two

Table 3-1

Parameter Settings for Pit Model Simulations

No.	Start mm/dd	Dissolved Oxygen Demand Benthic (g/m^2/d)	In Situ (g/m^3/d) Winter	 Summer	Channel Depth (m)	Turbulent Diffusion Scaled by K Factor
(Periodic boundary conditions)						
1	01/16	0.2	0.0010	0.014	4.06	1
2	01/16	0.2	0.0010	0.014	8.12	1
3	01/16	0.2	0.0010	0.014	12.18	1
4	01/16	0.2	0.0010	0.014	16.24	1
5	01/16	0.1	0.0005	0.007	12.18	1
6	01/16	0.3	0.0015	0.021	12.18	1
7	09/16	0.2	0.0010	0.014	12.18	1
(Non-periodic boundary conditions)						
8	01/01	0.2	0.0070	0.014	4.06	1
9	01/01	0.2	0.0070	0.014	8.12	1
10	01/01	0.2	0.0070	0.014	12.18	1
11	01/01	0.2	0.0070	0.014	16.24	1
12	10/28	0.2	0.0250	0.050	8.12	10
13	10/28	0.2	0.0250	0.050	8.12	1
14	10/28	0.2	0.0105	0.021	8.12	10
15	10/28	0.2	0.0105	0.021	8.12	1
16	10/28	0.2	0.0070	0.014	8.12	10
17	10/28	0.2	0.0070	0.014	8.12	1

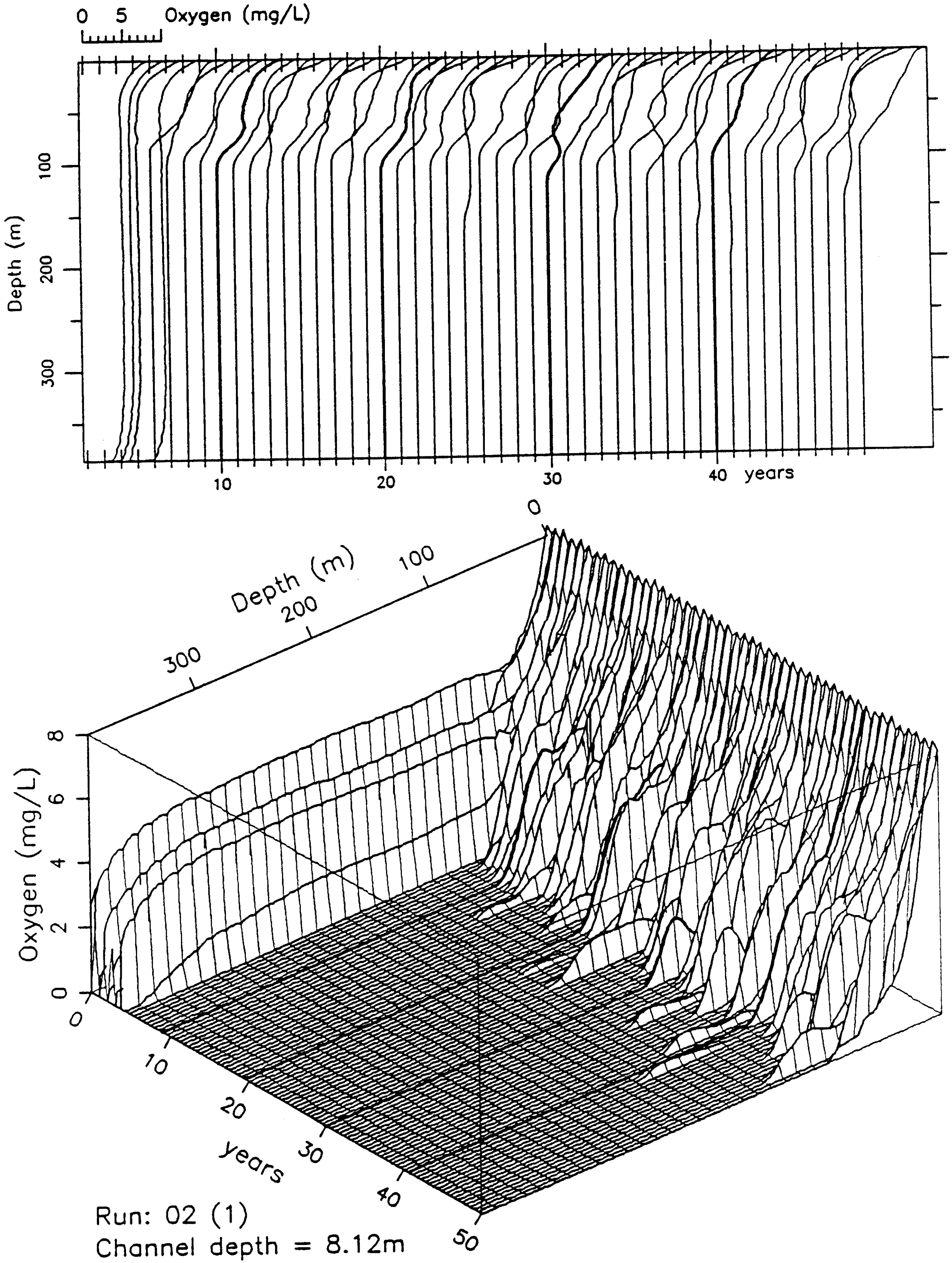


Run: 01 (1)
Channel depth = 4.06m
Oxygen fluxes = 0.2, 0.0070, 0.014
Start (mm/dd) = 01/16

09:24 Sep 13, 1990

FIGURE 3-1: ANNUAL VERTICAL PROFILES (TOP) AND DEPTH-TIME SURFACE (BOTTOM) OF DISSOLVED OXYGEN FROM SIMULATION 1

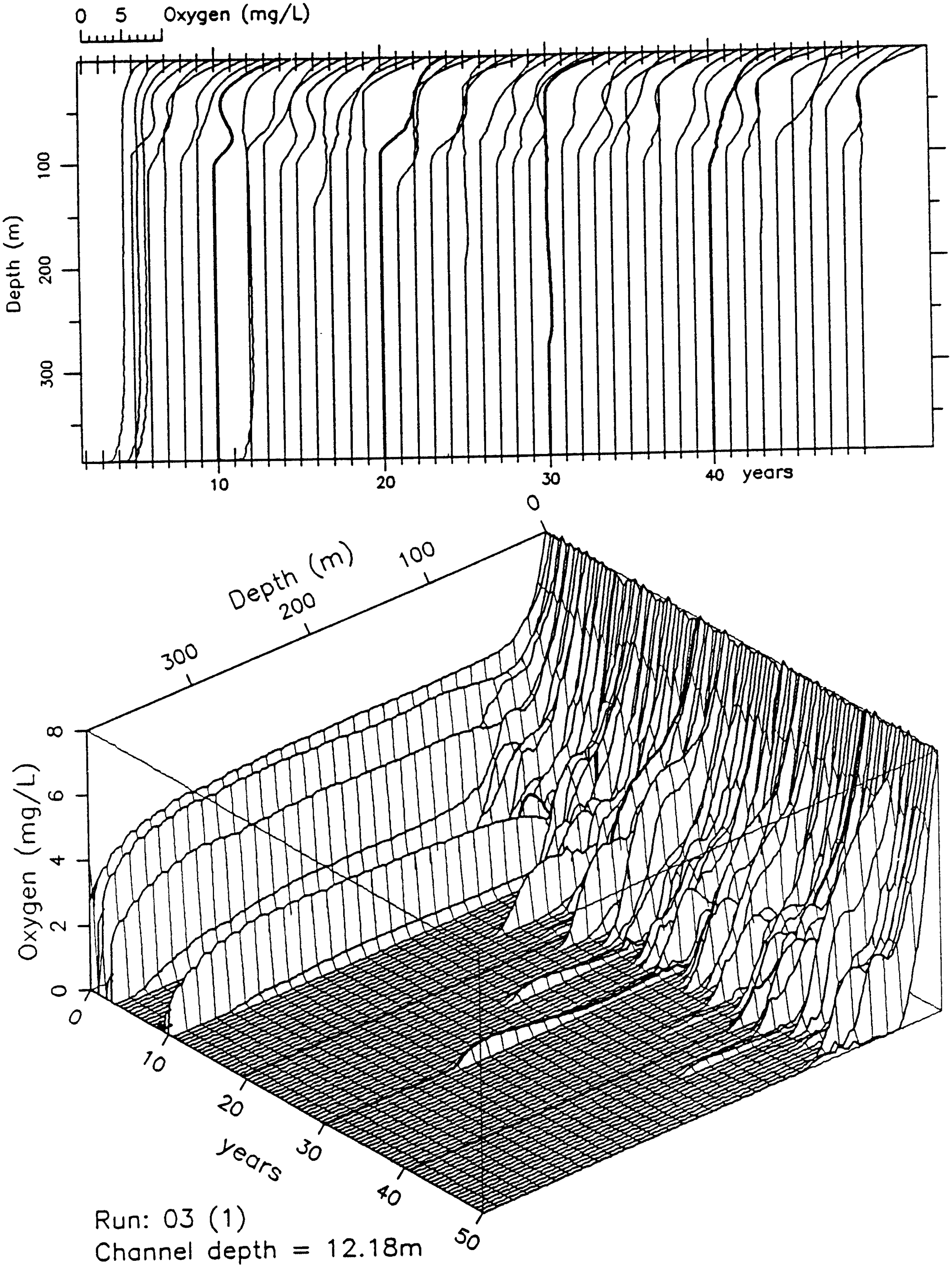
DB-R0022



Run: 02 (1)
Channel depth = 8.12m
Oxygen fluxes = 0.2, 0.0070, 0.014
Start (mm/dd) = 01/16

10:31 Sep 13, 1990

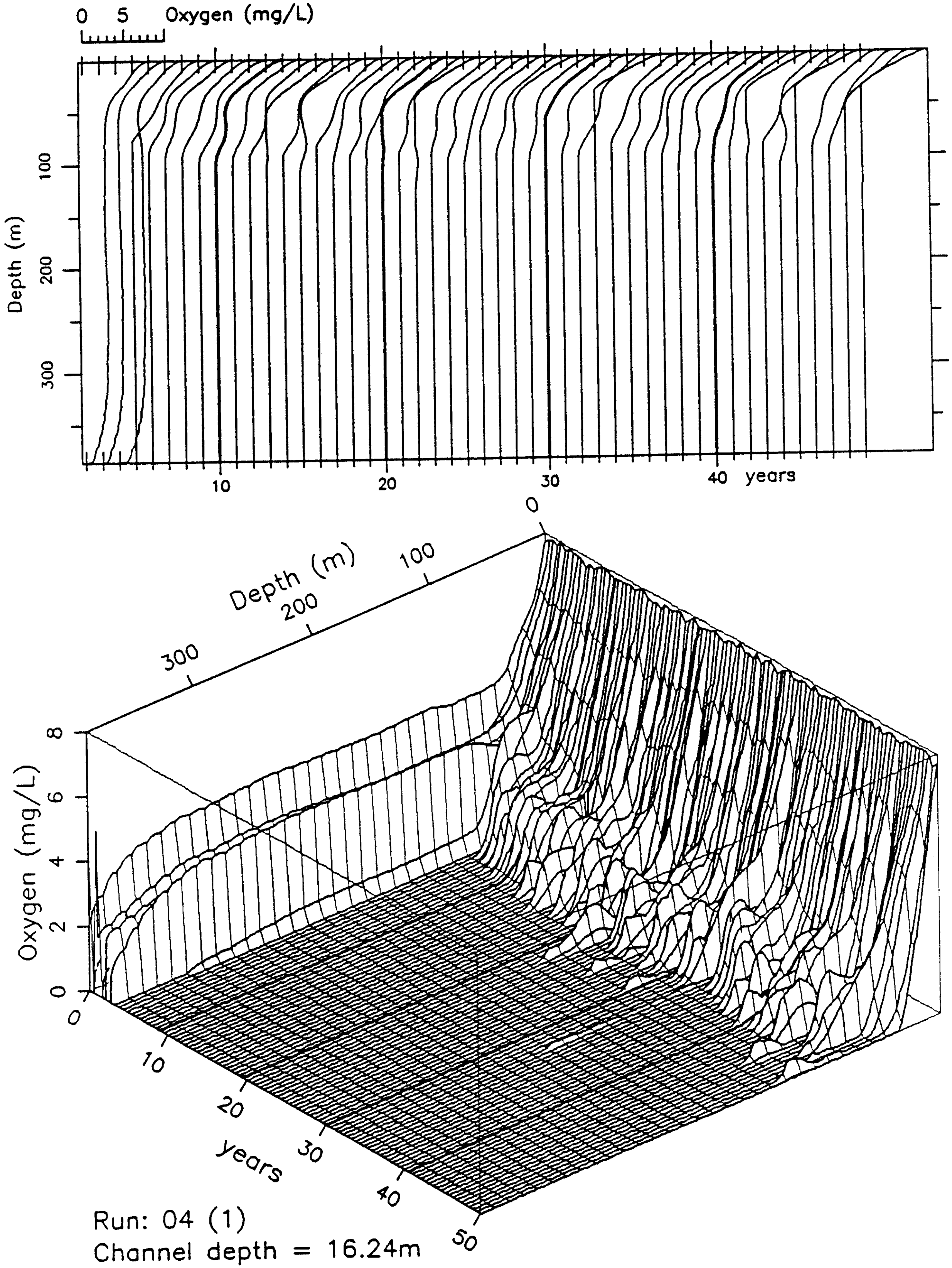
FIGURE 3-2: ANNUAL VERTICAL PROFILES (TOP) AND DEPTH-TIME SURFACE (BOTTOM) OF DISSOLVED OXYGEN FROM SIMULATION 2



Run: 03 (1)
Channel depth = 12.18m
Oxygen fluxes = 0.2, 0.0070, 0.014
Start (mm/dd) = 01/16

11:51 Sep 13, 1990

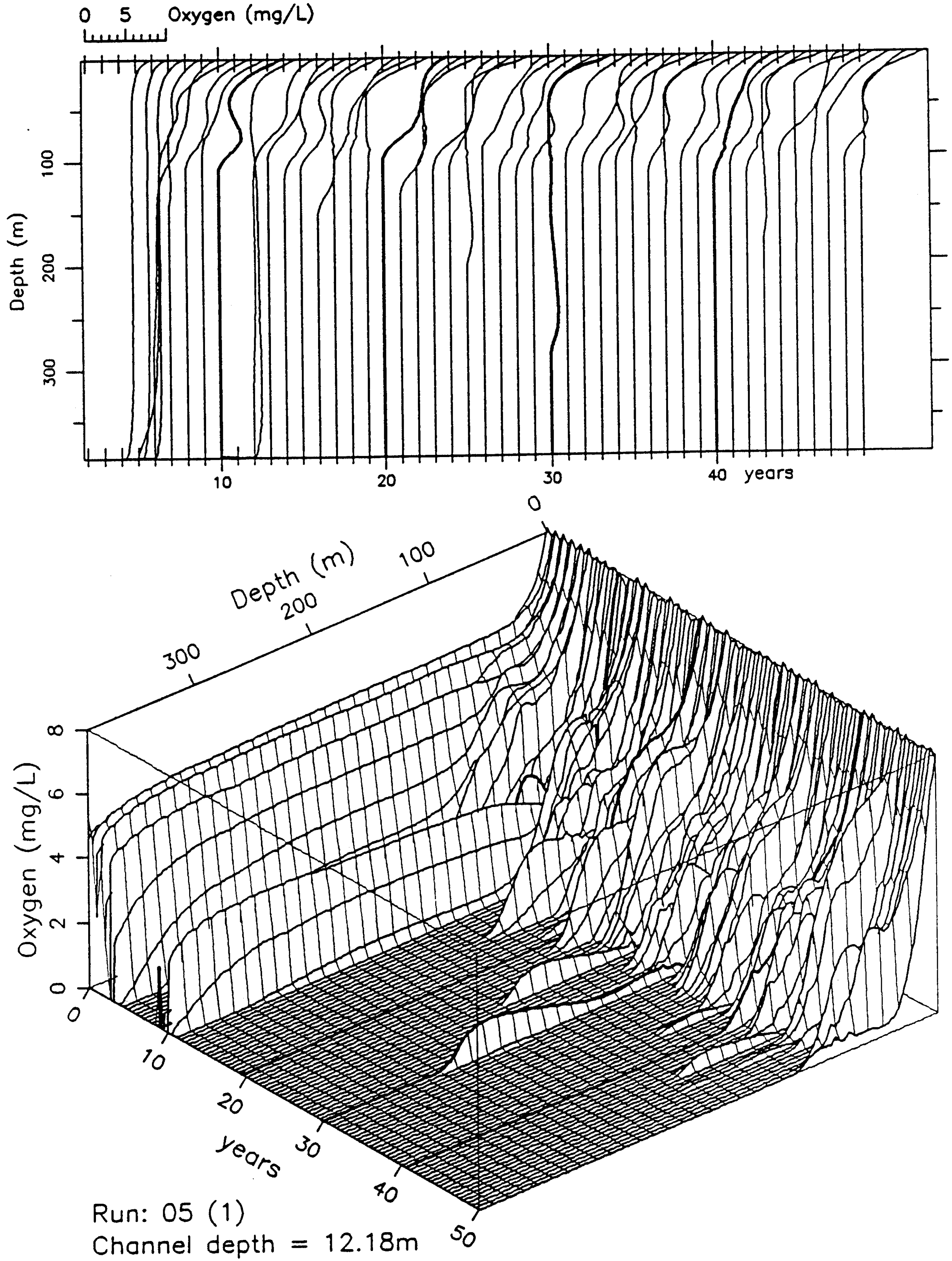
FIGURE 3-3: ANNUAL VERTICAL PROFILES (TOP) AND DEPTH-TIME SURFACE (BOTTOM) OF DISSOLVED OXYGEN FROM SIMULATION 3



Run: 04 (1)
Channel depth = 16.24m
Oxygen fluxes = 0.2, 0.0070, 0.014
Start (mm/dd) = 01/16

15:33 Sep 13, 1990

FIGURE 3-4: ANNUAL VERTICAL PROFILES (TOP) AND DEPTH-TIME SURFACE (BOTTOM) OF DISSOLVED OXYGEN FROM SIMULATION 4



Run: 05 (1)
Channel depth = 12.18m
Oxygen fluxes = 0.1, 0.0035, 0.007
Start (mm/dd) = 01/16

16:41 Sep 13, 1990

FIGURE 3-5: ANNUAL VERTICAL PROFILES (TOP) AND DEPTH-TIME SURFACE (BOTTOM) OF DISSOLVED OXYGEN FROM SIMULATION 5

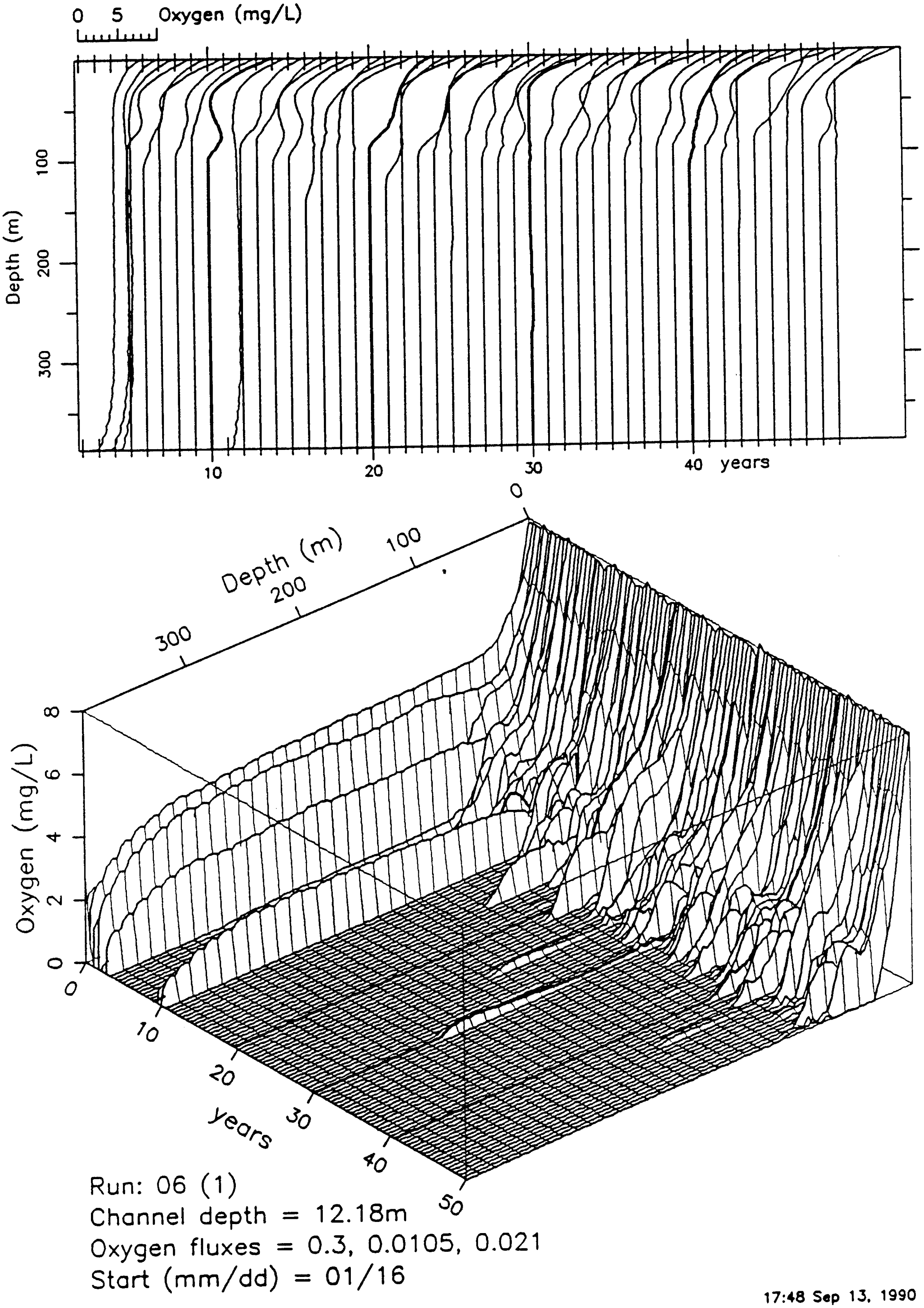


FIGURE 3-6: ANNUAL VERTICAL PROFILES (TOP) AND DEPTH-TIME SURFACE (BOTTOM) OF DISSOLVED OXYGEN FROM SIMULATION 6

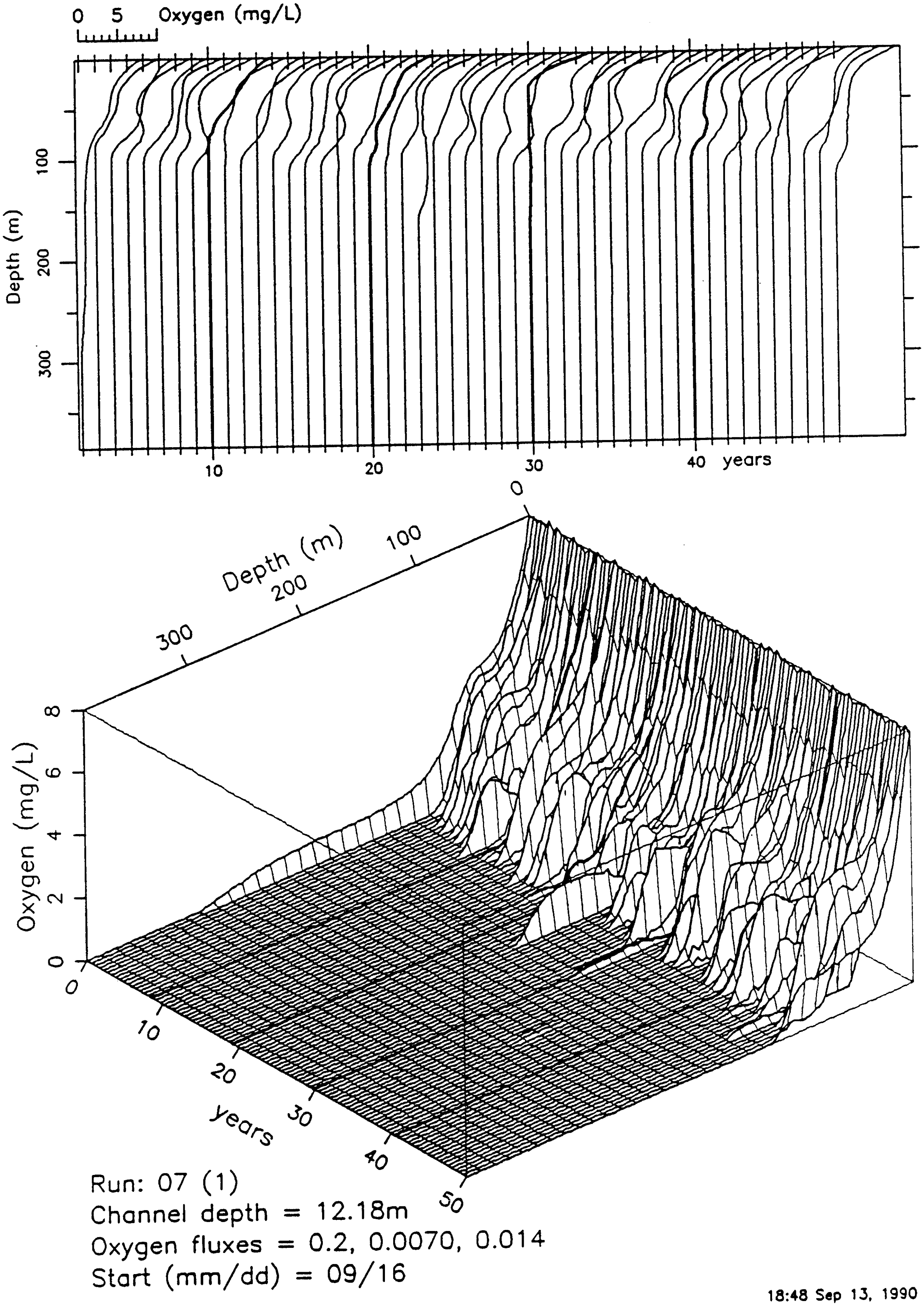


FIGURE 3-7: ANNUAL VERTICAL PROFILES (TOP) AND DEPTH-TIME SURFACE (BOTTOM) OF DISSOLVED OXYGEN FROM SIMULATION 7

sets of dissolved oxygen, temperature and salinity per month. A digital, weighted moving-average filter was applied in the time domain (Graham, 1963), prior to plotting, to filter out fluctuations at periods less than a subsampling rate of two profiles per year.

Comparing Figure 3-5 and 3-6 we see that varying the oxygen uptake rates by a factor of three has little impact on the final distribution of oxygen in the pit.

Some general features are common to the results from most of the simulations. After 50 years, the vertical oxygen distribution consists of an oxygenated surface layer that extends down to between 150 and 200 m. Maximum dissolved oxygen levels occur at the surface with values decreasing downward to anoxic conditions in the deeper layers.

To further refine the model, ten simulations (runs 8 to 17) were completed using boundary conditions generated by a stochastic model discussed in Appendix 1. The duration of each run was 200 years. Parameter settings are given in Table 3-1. The results of these runs are presented in Figure 3-8 to 3-17, which consist of time-series plots of dissolved oxygen at 4 meter intervals. Points are plotted semi-monthly, and the two ticks on each vertical axis corresponds to 5 and 10 mg/l. The figures reveal that oxygen levels down to 24 metres are generally greater than 5 mg/l.

Conclusions

The results of the simulations permit the following conclusions to be reached concerning the distribution of water properties in the Island Copper open pit mine:

(1) The dissolved oxygen level in the pit from the surface to a depth of 25 m maintains a mean value above 5 mg/l. Below this depth the oxygen level decreases rapidly to a mean value near 0 mg/l at about 100 m.

(2) The primarily anoxic conditions that exist from 100 m to the bottom are perturbed by episodic intrusions of oxygenated water that occur, on average, every 15 to 30 years, elevating the oxygen level to above 5 mg/l at all depths.

(3) Rare events - occurring once or twice in 200 years - result in anoxic conditions from 25 m to the bottom of the pit.

(4) The final DO profiles are similar for channel depths between about 4 and 16 m; thus, a shallow wide channel appears to be an acceptable alternative with no

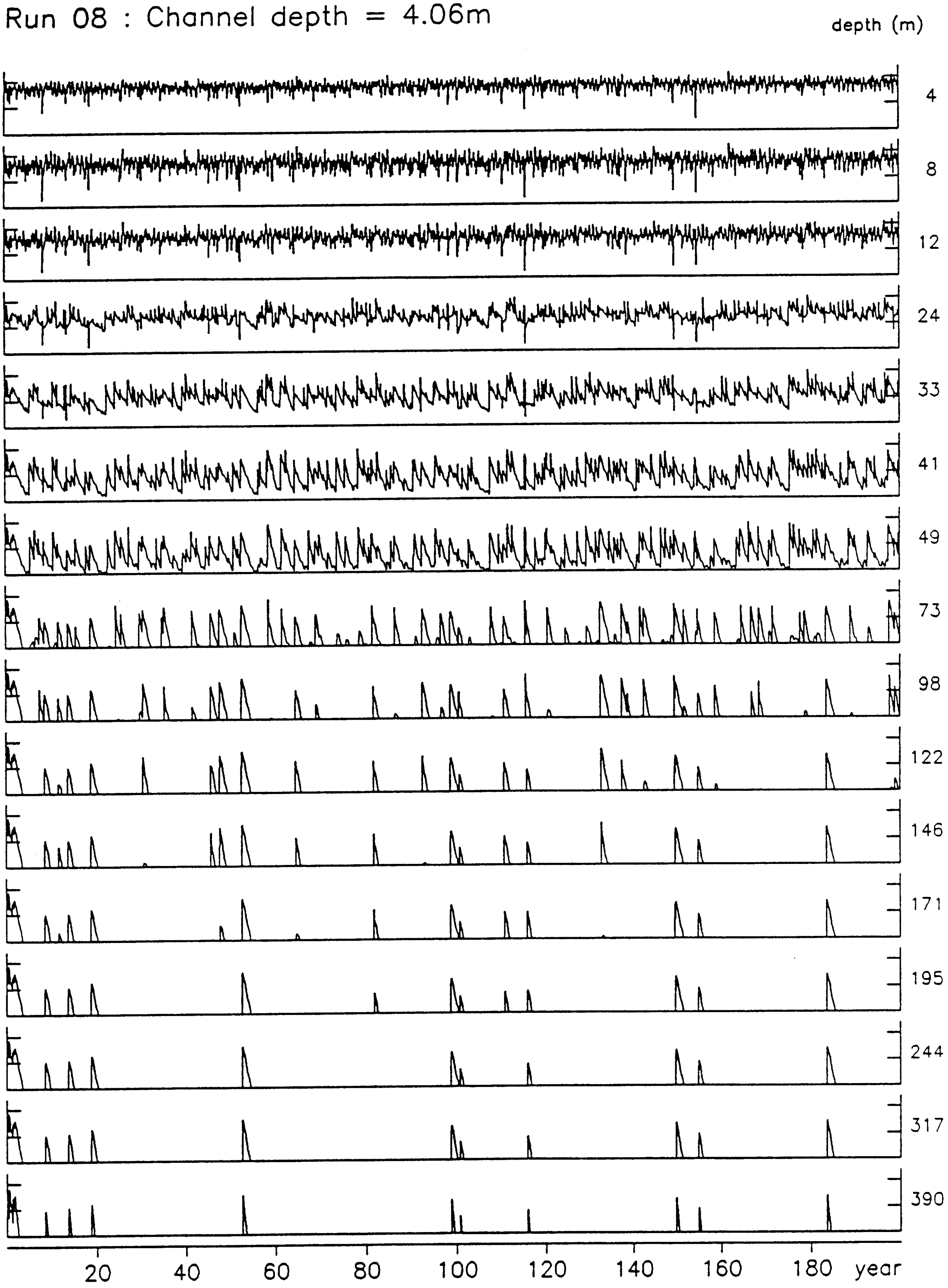


FIGURE 3-8: TIME SERIES DISSOLVED OXYGEN CONCENTRATION AT 4.0 m. INTERVALS FROM SIMULATION 8

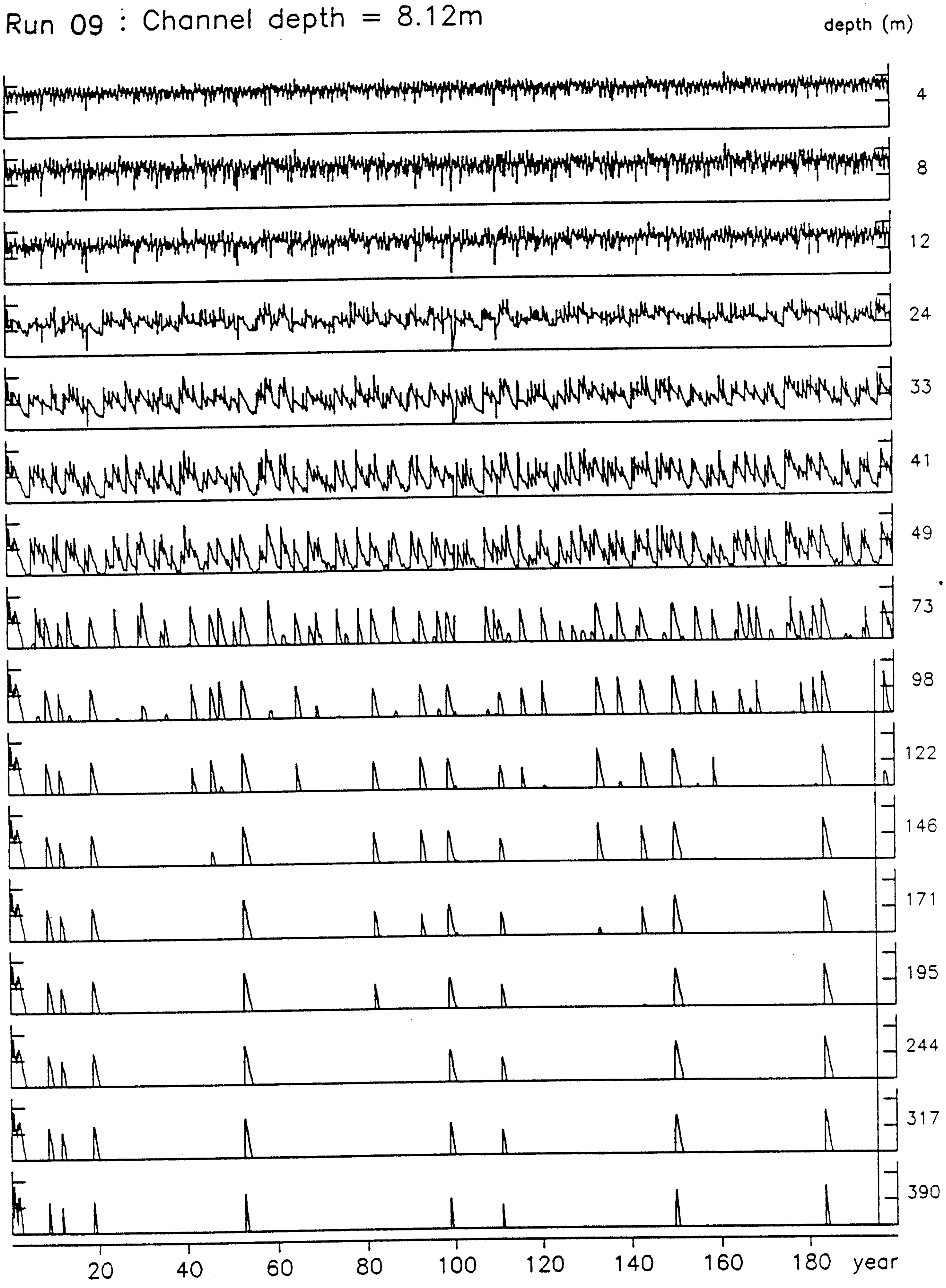


FIGURE 3-9: TIME SERIES DISSOLVED OXYGEN CONCENTRATION AT 4.0 m. INTERVALS FROM SIMULATION 9

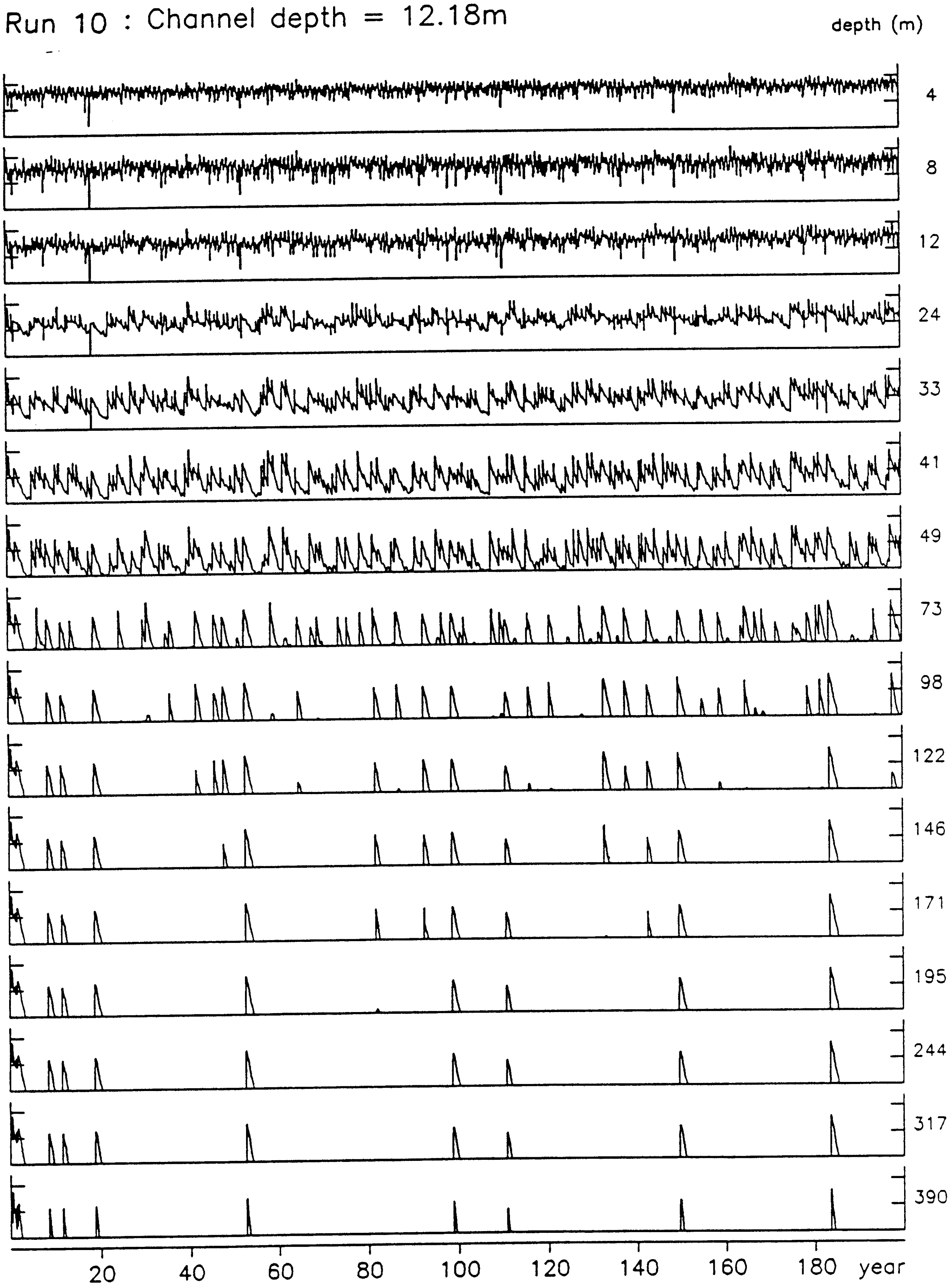


FIGURE 3-10: TIME SERIES DISSOLVED OXYGEN CONCENTRATION AT 4.0 m. INTERVALS FROM SIMULATION 10

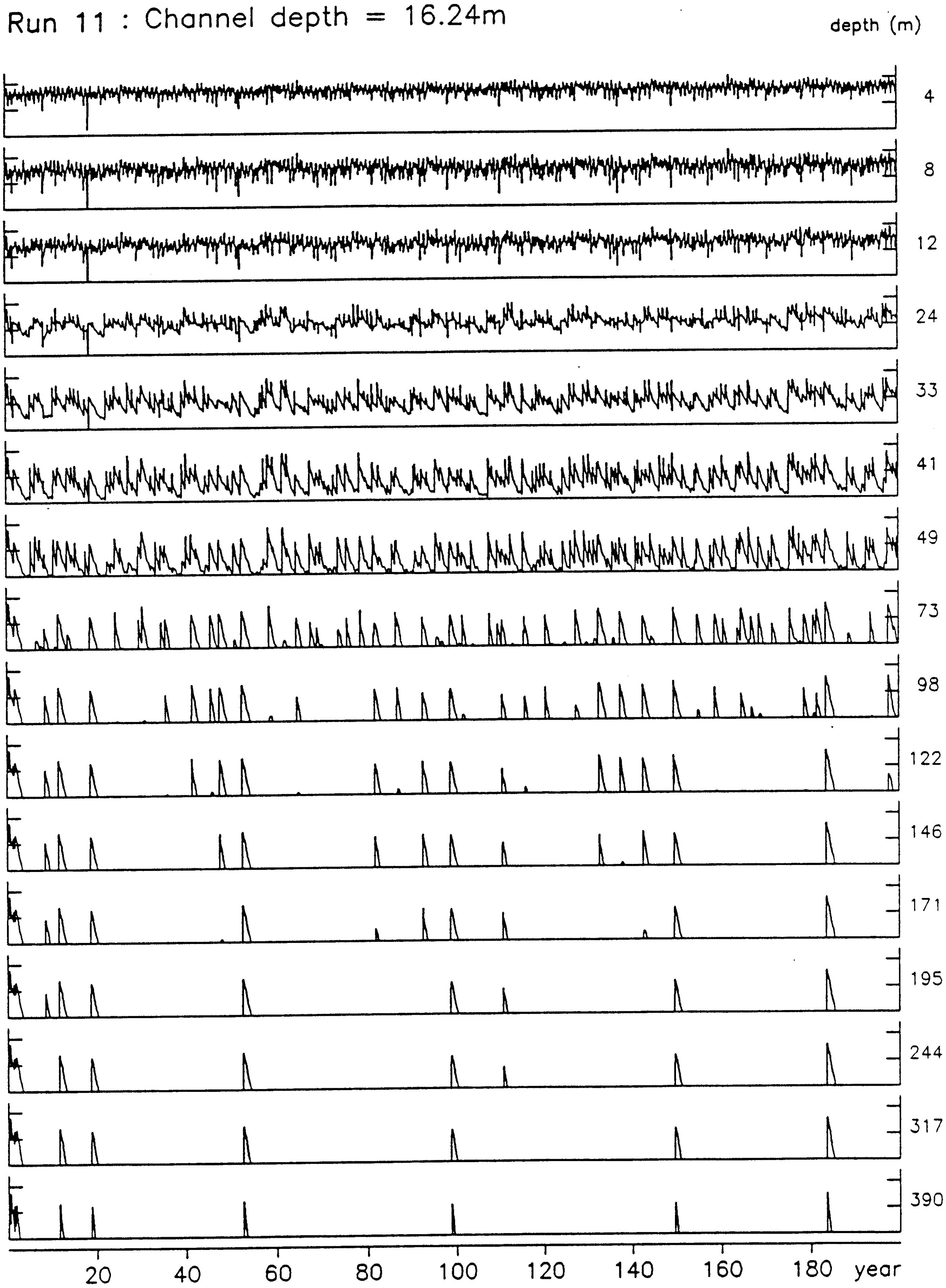


FIGURE 3-11: TIME SERIES DISSOLVED OXYGEN CONCENTRATION AT 4.0 m. INTERVALS FROM SIMULATION 11

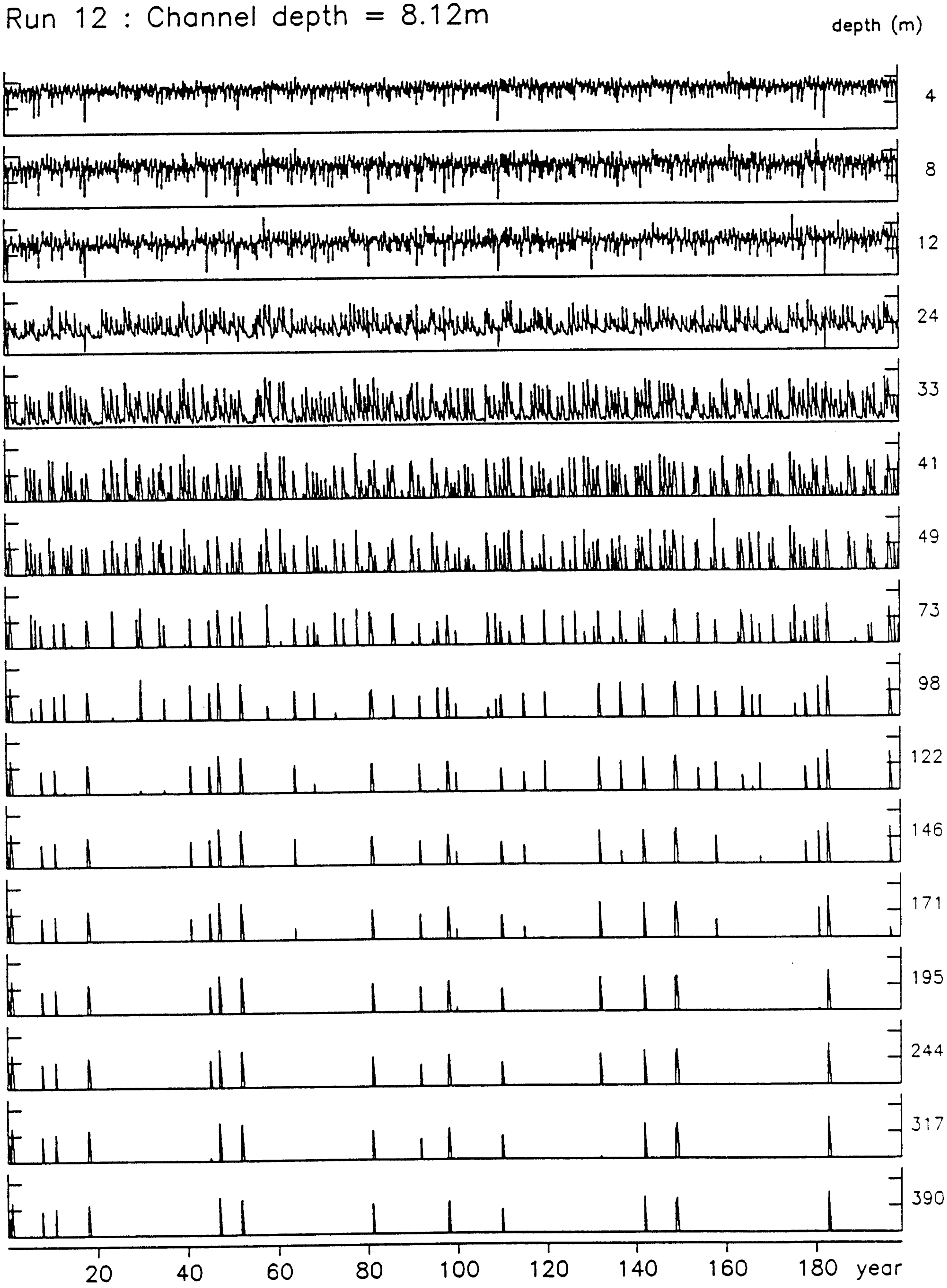


FIGURE 3-12: TIME SERIES DISSOLVED OXYGEN CONCENTRATION AT 4.0 m. INTERVALS FROM SIMULATION 12

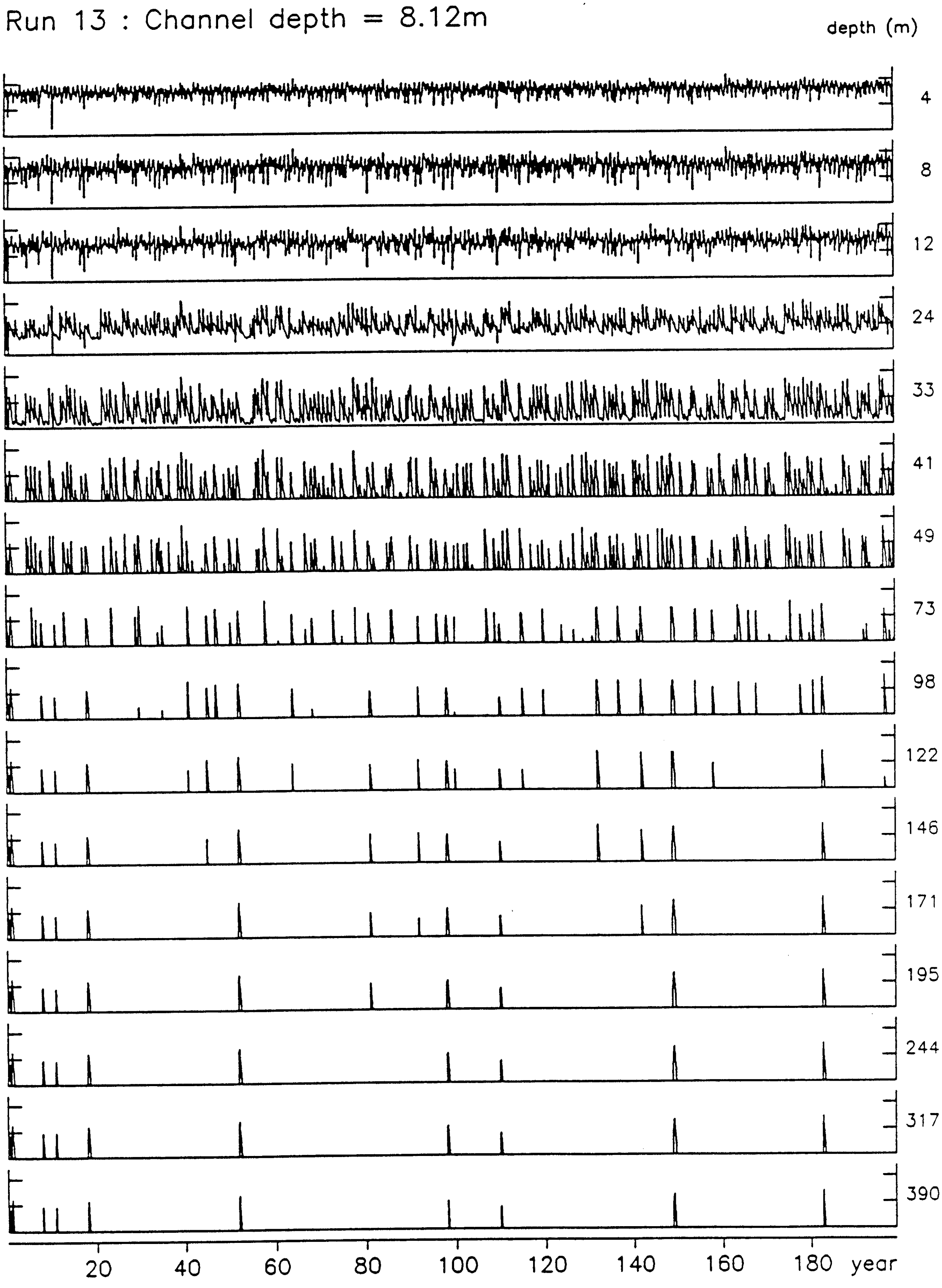


FIGURE 3-13: TIME SERIES DISSOLVED OXYGEN CONCENTRATION AT 4.0 m. INTERVALS FROM SIMULATION 13

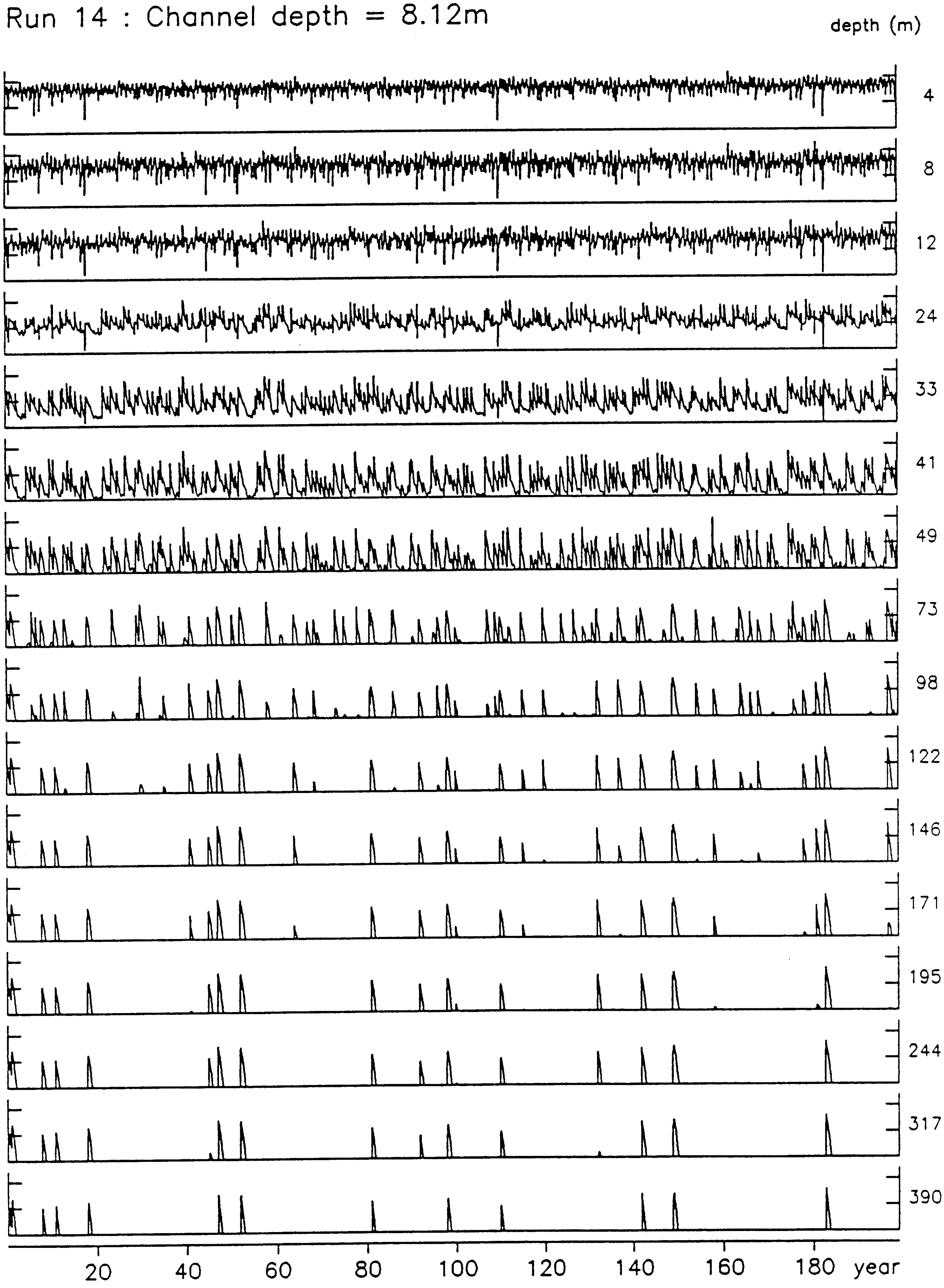


FIGURE 3-14: TIME SERIES DISSOLVED OXYGEN CONCENTRATION AT 4.0 m. INTERVALS FROM SIMULATION 14

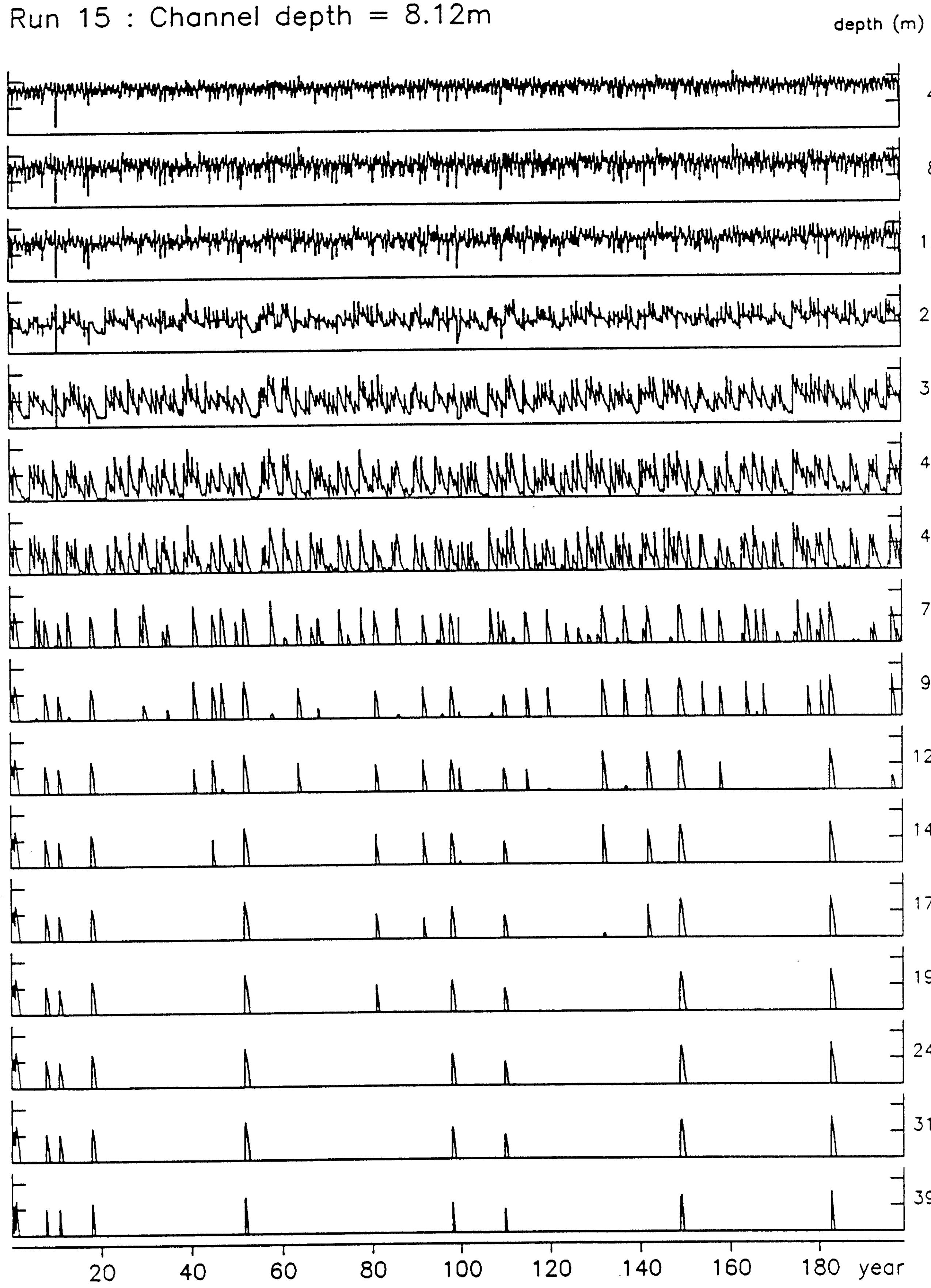


FIGURE 3-15: TIME SERIES DISSOLVED OXYGEN CONCENTRATION AT 4.0 m. INTERVALS FROM SIMULATION 15

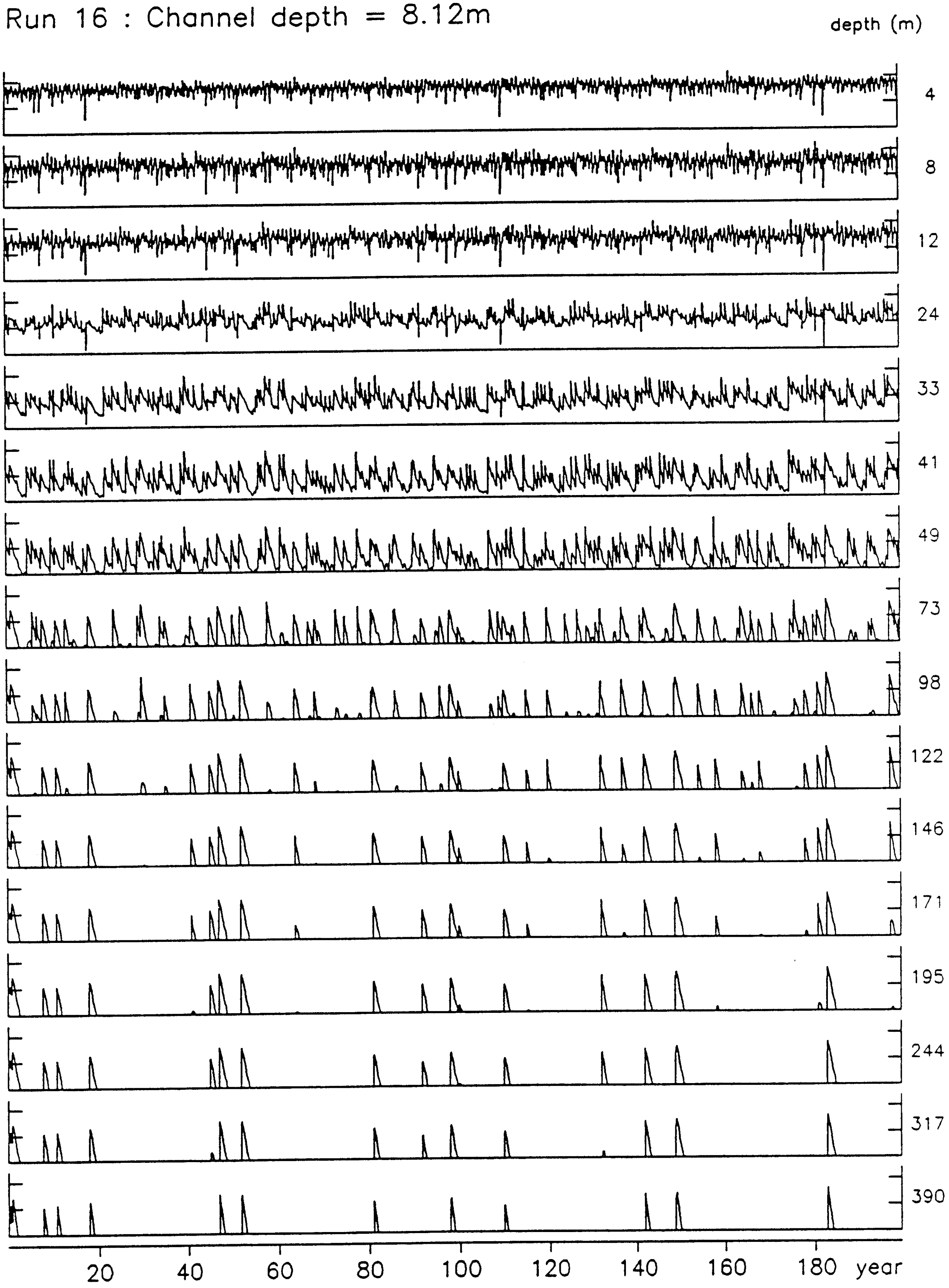


FIGURE 3-16: TIME SERIES DISSOLVED OXYGEN CONCENTRATION AT 4.0 m. INTERVALS FROM SIMULATION 16

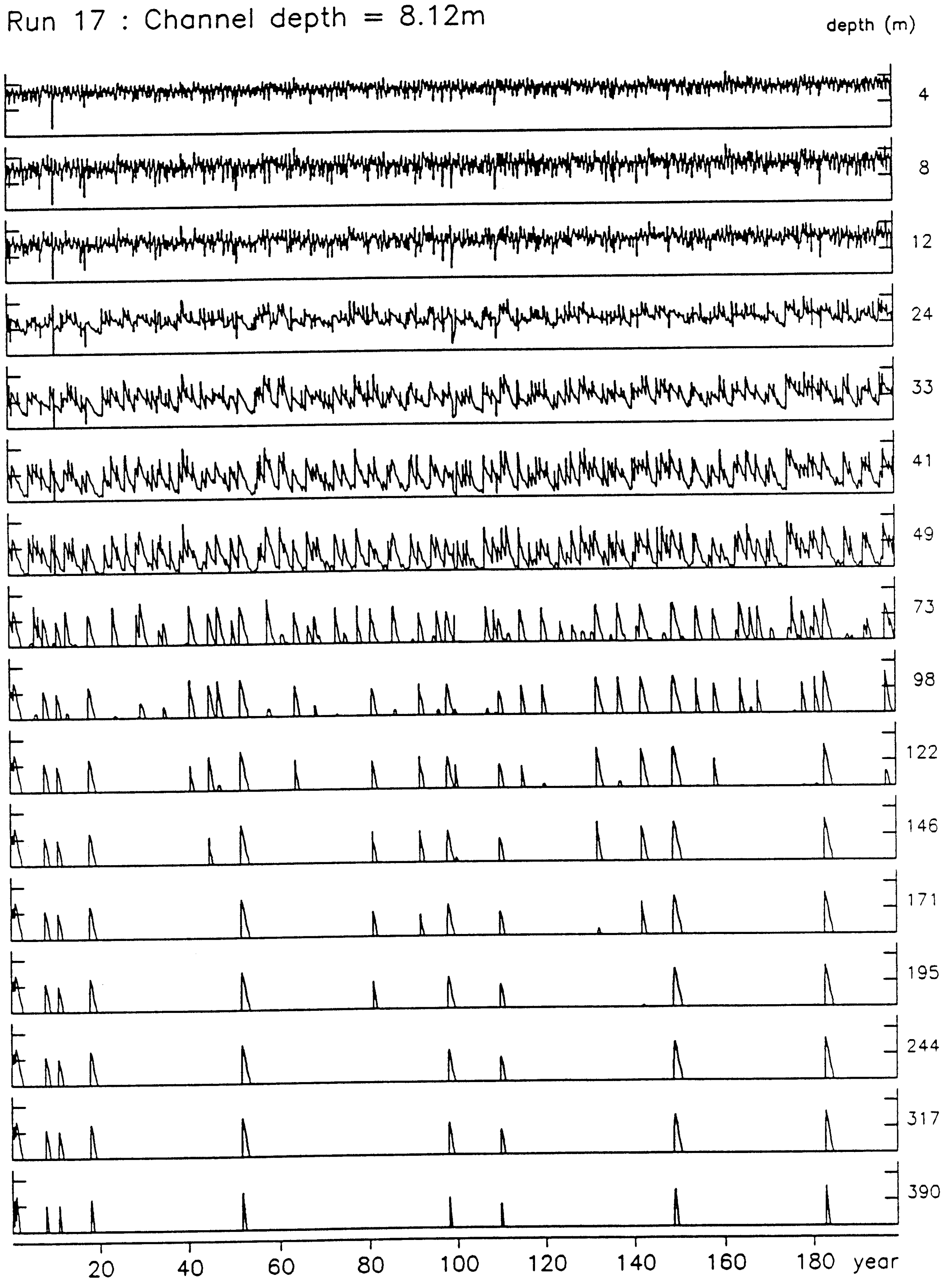


FIGURE 3-17: TIME SERIES DISSOLVED OXYGEN CONCENTRATION AT 4.0 m. INTERVALS FROM SIMULATION 17

clear advantages associated with a deeper channel within the range of depths that were modelled.

(5) A channel area of 4,000 ft^2 (372 m^2) yielded maximum currents of about 1.5 m/s for spring tides which are acceptable for navigation. Water exchange between Rupert Inlet and the pit also achieves 90 to 95% of the tidal prism for the pit and thus there is little or no choking of flow in a channel of this area. A channel design of 200 ft wide by 20 ft deep would provide the necessary area and may meet construction criteria.

(6) Providing annual, periodic boundary data to the pit model results in a stable distribution of oxygen in the pit after about 35 to 40 years. The final distribution exhibits annual variability, but is constant from year to year.

(7) The final distribution of oxygen is insensitive to the range of oxygen uptake rates used in the simulations, that is: 0.1 to 0.3 g/m^2 for the benthic rate, 0.0070 to 0.0105 g/m^3 for the background in situ rate, and 0.0070 to 0.021 g/m^3 for the in situ rate during the six month period of high productivity.

(8) The final distribution of oxygen is also insensitive to the time in the year that the pit is filled. Beginning with minimum density water in the channel, 30 to 40 years were required to reach the same state as occurs when the pit is filled with maximum density water.

(9) The long-term (greater than 10 year) distribution of oxygen is also insensitive to the time during the year that the pit is filled. Beginning in early winter with minimum density water in the channel, about 10 years were required to reach the same steady state as occurs when the pit is filled during early Fall with water of maximum density. The short term evolution of the pit (less than 10 years), however, is strongly affected by the time of year during which the pit is filled.

The model forecasts the eventual development of a deep-water anoxic zone, an oxygenated near-surface zone and a potential sporadic overturn of anoxic water being carried toward the surface. The model gives a good account of the physicochemical processes involved but is limited in its ability to forecast events which could have short and long term consequences to the biology of the newly formed inlet.

The following addresses uncertainties associated with the flooding.

Biological

Firstly, the model forecasts in the short term that the pit will fill with seawater over a period of 40 days. Seawater entering this system will contain plankton and some larger marine organisms together with a concentration of about 10^5 to 10^6 bacteria/ml. Under any conditions in which seawater is suddenly 'captured' and retained, there is an initial mortality of much of the biota. This leads to bacterial decomposition and an initial oxygen debt of several ppm. If the filling water contained a large spring phytoplankton bloom at the time of flooding, the oxygen debt could be very significant and surface values of 7 to 8 mg l/1 could drop to 2 to 4 mg/l which is lethal for some fish such as young salmon. Thus it would be advisable to use winter water, which is relatively free of plankton, for the filling process.

Following an initial drop of 1 or 2 ppm O_2 levels (assuming winter water for filling), surface levels will equilibrate with the atmosphere and the O_2 deficit in the deep water will commence according to the model's predictions.

In the long term the pit water will, to some extent, behave as a chemostat in which the tidal input of water is balanced by the tidal output, each tidal cycle (or 'pump') acting to enrich the biota and to withdraw from the biota. Colonization of benthic and pelagic species common to Rupert Inlet is expected to proceed rapidly under such conditions. However, one difference in the concept of a biological chemostat is that insufficient turbulence within the pit will cause sinking of some of the biota from the surface layers. Thus the pit will act in part as a nutrient trap, and it is this gradual accumulation of nutrients in the form of organic carbon compounds which will lead to the O_2 deficit in deep waters. Based on an annual phytoplankton productivity of about 150 g/cm^2/y, the decomposition of this material would proceed at an average rate of about 0.05 mg O_2/l/day, and it would then take about 32 years for all the oxygen to be consumed in the pit. In fact, as the model correctly predicts, the situation does not go to such an extreme event (i.e. a gross O_2 budget deficit) because atmospheric O_2 and photosynthetic O_2 are continually added to the surface layers and mixed to equilibrium concentrations, at least down to the seasonal pycnocline. However, the predicted model level of 5 mg O_2/l is at the threshold at which young salmon can become stressed (i.e. at < 5 mg O_2/l). It should therefore be emphasized that the 5 mg/l is to be taken as an average figure for the first 25 m, and near-surface levels can be expected to be at least 7 mg/l. This is a satisfactory level for young salmon which might enter the pit waters.

A biological problem arises if high salinity water enters the pit, sinks toward the bottom, and thus forces anoxic water toward the surface. This event and its potential frequency is dealt with in the model. Several scenarios of this affect can be developed, depending on the size and frequency of the anoxic upwelling. These are as follows:

Case A

Anoxic water penetrates to the euphotic zone and remains there, but below a surface oxygenated zone. This situation will not cause any mass mortality of the pelagic biota, although some benthic organisms living on the side of the pit and exposed to the anoxic water will die. However, a noticeable change in appearance of the water in the pit may be caused by the growth of purple bacteria (e.g. *Thiocapsay* sp.) within the euphotic zone at the depth at which H_2S is present.

Case B

A single pulse of anoxic water comes to the surface once every 20 years. This situation is not excluded by the boundary conditions of the model, and the initial pulse of anoxic water at the surface will be sufficient to kill most pelagic organisms (including fish) in the surface layers. Such an event would be similar to events in Nitinat Lake (and in other natural locations in world oceans, such as the south coast of India) where anoxic waters rising from depth cause fish mortalities. However, this effect would not be expected to occur outside the pit waters because H_2S is quickly destroyed by oxygen, and the tidal turbulence of the channel would probably destroy most of the toxic effect. In any event, the volume of water leaving the pit is a very small fraction of Rupert Inlet.

As the pit will act as a nutrient trap, it is probably better not to encourage excessive nutrient enrichment of the deep waters. This can be avoided to some extent by constructing a shallow channel which will draw water from Rupert Inlet at a depth above the seasonal nutricline (i.e. less than about 10 m). During the 40 day filling period some form of screen or net may be required across the channel to prevent larger organisms from entering the pit during filling and then dying due to extreme turbulence.

Chemical

Chemical considerations associated with flooding of the open pit include not only the oxygen concentrations but the fate of dissolved metal levels.

Three stages in the chemical evolution of the open pit are envisaged after flooding: (a) initial filling with oxygenated seawater at pH=8; (b) gradual consumption of oxygen and development of suboxic or dysaerobic conditions; (c) establishment of steady-state, and permanent anoxia in the deep waters, punctuated at depth by rare additions of oxygenated water. Stages (a) and (b) will evolve relatively rapidly, according to the model (i.e. on the order of a few years, or possibly less). During these initial (pre-anoxic) stages, there is potential for the dissolution of soluble metal salts formed by alteration of sulphides on the walls of the pit prior to flooding. The resulting concentrations of metals will be constrained by the solubility of their least soluble salts at ambient pH (~8), the available surface area of alteration products on the pit walls, and dilution by the pit water. It is difficult, if not impossible, to predict the concentrations of Zn, Cu and Cd which could be present under such conditions given the uncertainty in estimating the amount of metal salts available for solution. It is fair to predict that dissolved metals levels in the flooded pit may reach levels significantly higher (obviously depending on the supply from the walls) than in the incoming Rupert Inlet water. However, once anoxia is established, metal levels in deep water should drop precipitously. Zn, Cu and Cd sulphides are extremely insoluble, and although they have slightly different chemical behaviours (e.g. speciation), it is expected that the hydrogen sulphide (as HS-) concentration will become quite high relatively quickly in the pit. Under such conditions, dissolved Zn, Cu and Cd concentrations should be strongly attenuated. The degree of the attenuation will be a function of [HS-], complexation with organic ligands (should be relatively minor), complexation with inorganic ligands (major ions will compete with HS-), but the sulphide can be expected to dominate (see Jacobs *et al.*, 1985). In addition, at the pH of seawater, sulphide precipitation will provide the upper limit on Zn, Cu and Cd solubility rather than the solubility of hydroxide or carbonate phases (see Rescan, 1989, pp. 3-15 ff, for a review).

3.3.3.2 Pit Walls Above Sea Level

Exposed walls of the pit that will be above the high water mark may generate some acidic drainage. To evaluate the likelihood of this occurring, samples of wall rock were analyzed and the net neutralizing potential (NNP) was determined. Table 3-2 is a tabulation of the analytical results; Figure 3-18 is a visual presentation of the data. Areas with high NNP are shown in blue and areas with lower NNP are shown in red. It is clear from this study that there are two zones on the pit walls with very low NNP. Geological mapping of the walls does not show any relation to the NNP. The reactivity and the resulting production of oxidation products will be difficult to quantify. The flooding of the pit with seawater, which will flush twice daily, should minimize impacts.

3.3.4 Mill Tailings

Tailings from the Island Copper concentrator are discharged into Rupert Inlet via a submarine outfall system. The impact of this discharge on the environment has been monitored extensively with results reported to the Regulatory agencies annually.

Closure of the tailings system will include post shutdown monitoring of Benthic recolonization and removal of shoreline tailings control works. Pre- and post-closure monitoring will be conducted for four years: two years of operational evaluation followed by two years of post-discharge monitoring. The pre-closure monitoring program will be similar to that presently being carried out under Waste Management Permit P-379. The planned post-closure monitoring program is detailed in Table 3-3.

Table 3-2

Pit Wall Acid Potential Test Results

Sample	Pyrite	NP	APP	Sulphur	NNP
19512	2.00	92.77	90.34	2.95	2.43
19513	3.00	22.55	94.02	3.07	-71.47
19514	1.00	29.22	76.26	2.49	-47.04
19515	1.00	35.12	144.55	4.72	-109.43
19516	5.00	31.52	112.39	3.67	-80.87
19517	3.00	25.53	83.30	2.72	-57.77
19518	2.00	25.12	97.39	3.18	-72.27
19519	1.00	43.57	41.34	1.35	2.23
19520	2.00	23.06	101.37	3.31	-78.31
14241	1.00	34.30	47.50	1.55	-13.20
14242	1.00	70.30	47.50	1.55	22.80
14243	1.00	24.60	16.80	.55	7.80
14244	1.00	60.30	14.70	.48	45.60
14245	1.00	40.20	12.90	.42	27.30
19511	1.00	28.84	79.93	2.61	-51.09
14246	1.00	70.10	23.60	.77	46.50
14247	1.00	70.10	19.30	.63	50.80
14248	1.00	74.90	23.90	.78	51.00
14249	2.00	38.70	8.60	.28	30.10
14250	1.00	41.00	6.70	.22	34.30
14251	1.00	34.60	.60	.02	34.00
14252	1.00	84.50	3.40	.11	81.10
14253	1.00	34.30	4.30	.14	30.00
14254	1.00	32.00	5.20	.17	26.80
14255	1.00	47.20	2.50	.08	44.70
19852	1.00	31.26	33.08	1.08	-1.82
19851	2.00	16.59	41.04	1.34	-24.45
19850	.00	17.10	23.15	.76	-6.05
19849	7.00	21.95	282.06	9.21	-260.11
19848	10.00	29.60	74.42	2.43	-44.82
19847	1.00	29.86	14.21	.05	15.65
14269	3.00	25.27	138.73	4.53	-113.46
14270	5.00	6.89	245.91	5.03	-239.02
14271	3.00	12.76	143.32	4.68	-130.56

Table 3-2 (cont'd)

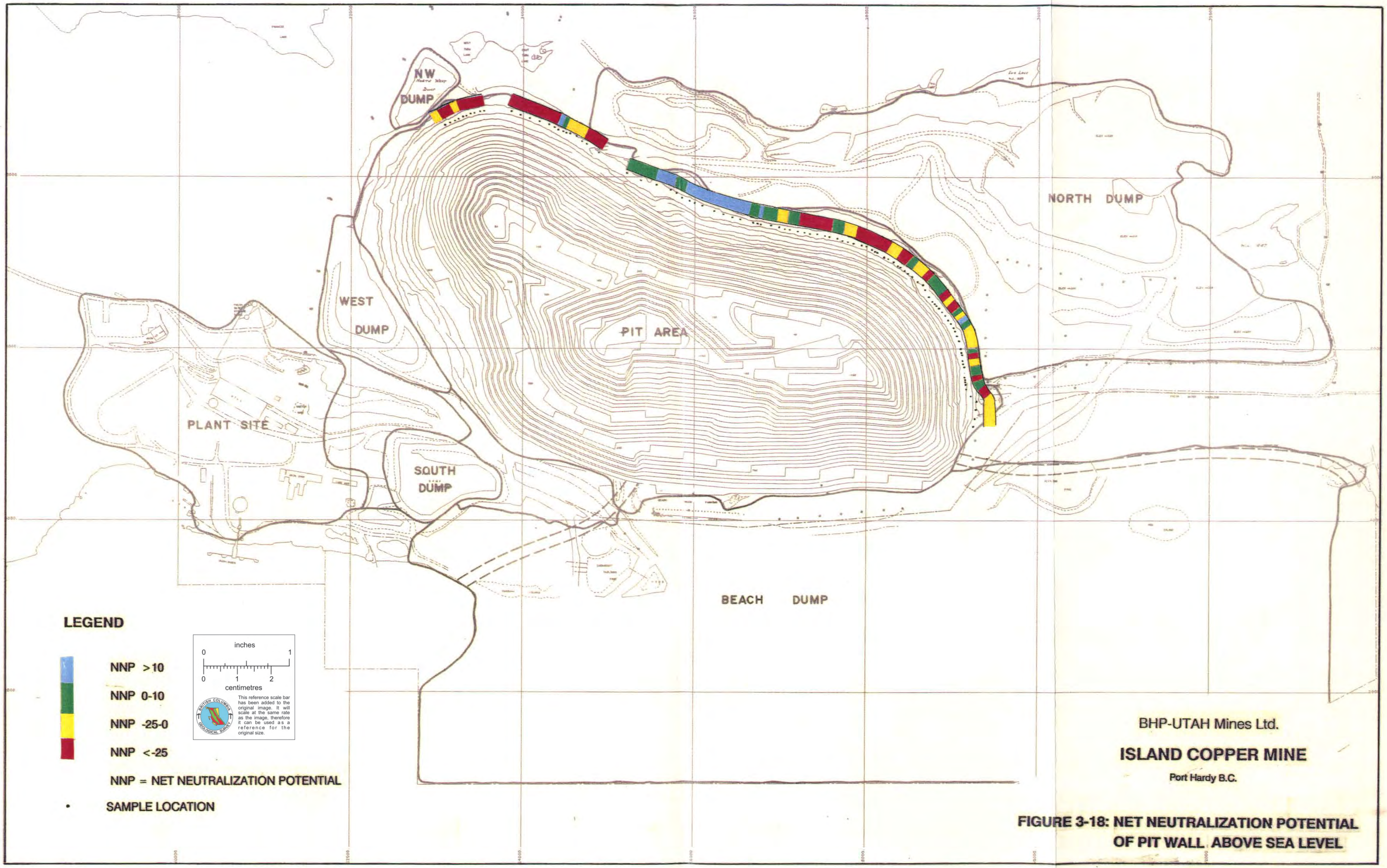
Pit Wall Acid Potential Test Results

Sample	Pyrite	NP	APP	Sulphur	NNP
14272	2.00	12.76	163.82	5.35	-151.06
14273	2.00	28.58	15.99	.52	12.59
14274	1.00	31.50	50.50	1.65	-19.00
14264	3.00	32.30	38.30	1.25	-6.00
14265	3.00	35.90	20.80	.68	15.10
14266	2.00	28.20	200.30	6.54	-172.10
14267	2.00	39.70	96.80	3.16	-57.10
14268	5.00	36.10	63.70	2.08	-27.60
19861	1.00	18.12	139.00	4.54	-120.88
19862	2.00	15.57	78.10	2.55	-62.53
19863	1.00	28.58	139.96	4.57	-111.38
19864	1.00	38.28	18.19	.59	20.09
14275	1.00	22.30	48.70	1.59	-26.40
14276	3.00	14.10	158.00	5.16	-143.90
14277	1.00	25.40	6.49	.21	18.91
14278	1.00	24.10	117.00	3.82	-92.90
14279	3.00	72.30	56.00	1.83	16.30
14280	1.00	48.20	49.30	1.61	-1.10
14259	2.00	45.10	146.40	4.78	-101.30
14260	1.00	46.90	60.30	1.97	-13.40
14261	1.00	17.90	127.10	4.15	-109.20
14262	1.00	39.50	9.20	.30	30.30
14263	1.00	28.90	3.40	.11	25.50
14256	1.00	27.90	.90	.03	27.00
14257	1.00	34.60	23.60	.77	11.00
14258	2.00	44.60	18.70	.61	25.90
19501	1.00	21.80	75.00	2.45	-53.20
19502	1.00	29.70	51.50	1.68	-21.80
19503	1.00	26.29	181.61	5.93	-155.32
19504	1.00	28.58	104.13	3.40	-75.55
19505	1.00	19.90	169.05	5.52	-149.15
19506	1.00	30.88	75.03	2.45	-44.15
19507	2.00	29.60	199.06	6.50	-169.46
19508	3.00	22.46	115.46	3.77	-93.00

Table 3-2 (cont'd)

Pit Wall Acid Potential Test Results

Sample	Pyrite	NP	APP	Sulphur	NNP
19509	2.00	34.45	105.96	3.46	-71.51
19510	2.00	37.26	57.27	1.87	-20.01
19842	1.00	33.83	35.53	1.16	-1.70
19843	3.00	36.65	57.27	1.87	-20.62
19844	3.00	13.27	73.50	2.40	-60.23
19845	2.00	36.24	39.20	1.28	-2.96
19865	1.00	41.34	19.36	.63	21.98
19866	2.00	10.72	77.79	2.54	-67.07
19867	1.00	27.45	58.49	1.91	-31.04
19881	1.00	20.59	64.31	2.10	-43.72
19882	3.00	19.82	285.12	9.31	-265.30
19883	3.00	35.84	247.45	8.08	-211.61
19884	1.00	26.18	52.98	1.73	-26.80
19885	1.00	58.71	79.01	2.58	-20.30
19886	2.00	93.02	65.23	2.13	27.79
19887	2.00	63.79	20.52	.67	43.27
19888	3.00	46.76	69.21	2.26	-22.45
19889	.01	41.17	83.61	2.73	-42.44
19890	5.00	31.26	95.24	3.11	-63.98
19891	7.00	22.37	169.97	5.55	-147.60
19892	2.00	31.01	81.46	2.66	-50.45
19893	3.00	28.97	105.35	3.44	-76.38
19894	5.00	26.43	163.35	5.34	-136.92
19895	5.00	29.33	125.26	4.09	-95.93
19896	2.00	16.77	63.09	2.06	-46.32
19897	10.00	19.57	90.65	2.96	-71.08
19898	1.00	21.00	202.43	6.61	-181.43
19899	1.00	26.43	69.21	2.26	-42.78
19900	2.00	24.14	67.68	2.21	-43.54
19870	2.00	22.62	49.00	1.60	-26.38
19871	1.00	25.41	20.24	.66	5.17
19872	3.00	18.81	112.70	3.68	-93.89



LEGEND

🟦 NNP >10

🟩 NNP 0-10

🟨 NNP -25-0

🟥 NNP <-25

NNP = NET NEUTRALIZATION POTENTIAL

• SAMPLE LOCATION

inches
0 1
0 1 2
centimetres

This reference scale bar has been added to the original image. It will scale at the same rate as the image, therefore it can be used as a reference for the original size.

BHP-UTAH Mines Ltd.

ISLAND COPPER MINE

Port Hardy B.C.

FIGURE 3-18: NET NEUTRALIZATION POTENTIAL OF PIT WALL ABOVE SEA LEVEL

Table 3-3

Island Copper Post-Discharge Monitoring of Tailings

Station/Frequency		Analysis
Marine Physical		
	Suspended sediment 5 stations (A, B, D, E & F) at standard depths - quarterly	NTU and gravimeter
Marine Chemical		
	Seawater Dissolved Metals 5 stations (A, B, D, E & F) at 0, 5, 10 & 30 metres from bottom - quarterly	Cu, Zn, Cd
Marine Biology		
(a)	Benthic - 24 stations annually	identify infauna from sediment samples tailings recovery
(b)	Benthic - 3 stations annually	Otter trawls for epi-fauna
(c)	Crabs - 6 stations annually - (June)	Crab populations and metal analysis
(d)	Mussels - 5 stations annually	Metal analysis

4. WATER
MANAGEMENT
FOR CLOSURE

4 - Water Management for Closure

4.0 WATER MANAGEMENT FOR CLOSURE

4.1 Introduction

Monitoring of the surface water flows in and around the Island Copper minesite has identified several drainages and seeps from the land dumps which are releasing above background levels of elements associated with acid drainage. It is not the intent of this section to detail the history of acid drainage at Island Copper, but to outline the strategies that have been used to mitigate environmental impacts and to describe closure strategies.

4.2 Acid Drainage Characterization

Three types of water flow from the Island Copper land dumps, each with its own characteristic water quality finger print. Water infiltrating a dump moves through the various material types and seeps from the dump toe, usually along the flow path of the original surface watercourse.

The first type of water passes through neutralizing strata which results in water quality similar to the pre-mine End Creek drainage (Table 4-1). The pH remains above 7.3 and dissolved copper, iron and molybdenum generally remain near background levels. Zinc and manganese concentrations are typically elevated.

The second type of water is only partially neutralized. Its quality appears similar to that of water contained in the North diversion ditch (Table 4-2). During fall and winter periods (i.e. periods of high precipitation) the neutralizing capacity of the dumps is overwhelmed, resulting in the drainage becoming acidic and containing elevated levels of dissolved metals.

The third type of drainage always remains acidic because the infiltrating water does not pass through neutralizing strata. An example is Eastern Most Outslope (EMO) drainage (Table 4-3). It should be observed that the pH of this drainage is close to 4.0 which is above the dissolution pH of iron hydroxide and below that of aluminium hydroxide. The white precipitate characteristic of this drainage predominantly consists of compounds of aluminum.

Table 4-1

Water Quality
Old End Creek (Ground Water Seep) RTC
1989

Date	pH	Dissolved Solids (mg/l)	Sulphate (mg/l)	Alkalinity as $CaCO_3$ (mg/l)	Total Ca (mg/l)	Total Mg (mg/l)	Dissolved Metals (μg/l)						
							Cd	Cu	Fe	Pb	Mn	Mo	Zn
Jan	7.3	-	360	74	130	14	4.1	25	69	1.0	230	14	840
Feb	7.9	-	440	120	450	91	4.7	12	46	5.1	480	7.9	990
Mar	7.6	740	400	120	150	18	2.9	16	37	1.0	430	12	610
Apr	7.8	-	460	120	170	21	3.5	15	17	2.6	470	11	670
May	7.9	-	520	180	210	28	2.9	11	18	3.1	750	14	510
June	7.9	1500	550	260	230	31	0.6	7.3	22	2.5	1300	7.0	130
July	-	-	-	-	-	-	-	-	-	-	-	-	-
Aug	-	-	-	-	-	-	-	-	-	-	-	-	-
Sept	7.9	1230	600	370	260	44	<0.1	7.4	19	3.6	1400	21	21
Oct	7.6	-	800	110	290	31	9.2	41	19	<2.0	500	18	1880
Nov	7.7	-	480	74	170	16	7.3	62	31	<2.0	420	13	1600
Dec	7.9	820	450	99	170	18	5.5	23	100	1.2	240	16	910

Table 4-2

Water Quality
North Diversion Ditch (NDD)
1989

Date	pH	Dissolved Solids (mg/l)	Sulphate (mg/l)	Alkalinity/ Acidity as $CaCO_3$ (mg/l)	Total Ca (mg/l)	Total Mg (mg/l)	Dissolved Metals (μg/l)						
							Cd	Cu	Fe	Pb	Mn	Mo	Zn
Jan	5.9	-	550	12	130	7.7	23	280	300	4.9	1890	3.0	4420
Feb	6.4	-	390	55	380	82	13	22	200	3.7	1070	4.2	2620
Mar	6.3	670	400	39	130	17	14	47	270	1.0	1300	4.5	2700
Apr	6.3	-	500	41	150	20	15	33	130	1.0	1320	4.8	2850
May	6.4	-	500	58	170	24	17	21	100	1.0	1570	5.0	2830
June	6.8	900	600	93	190	26	9.2	8.4	120	4.0	2060	4.3	2510
July	7.1	-	500	98	170	22	8.9	34	100	1.0	1100	3.2	-
Aug	6.8	-	400	140	200	28	3.3	5.2	640	2.6	1800	6.0	1200
Sept	7.1	1280	730	160	240	39	1.7	5.6	810	3.6	2700	7.3	980
Oct	4.3	-	880	-	180	28	89	2470	890	57	-	3.6	16600
Nov	5.0	-	680	3	200	28	60	480	240	13	4000	6.0	9100
Dec	5.2	910	650	(25)	160	22	35	540	310	15	2900	3.6	5800

( ) **Acidity**

Table 4-3

Water Quality
Eastern Most Outslope (EMO)
1989

Date	pH	Dissolved Solids (mg/l)	Sulphate (mg/l)	Acidity as $CaCO_3$ (mg/l)	Total Ca (mg/l)	Total Mg (mg/l)	Dissolved Metals (μg/l)						
							Cd	Cu	Fe	Pb	Mn	Mo	Zn
Jan	4.1	-	1700	330	420	42	14	980	290	2.5	7000	4.8	9300
Feb	4.1	-	1450	370	1000	240	24	670	320	3.7	11000	2.4	10900
Mar	3.8	2930	1900	490	450	59	10	1100	290	1.0	11100	2.4	13700
Apr	4.1	-	1900	530	450	67	9.2	1260	550	1.0	12700	3.6	14000
May	4.0	-	2200	610	480	78	20	910	570	2.5	14530	5.0	15890
June	4.0	3000	2200	533	450	79	16	610	500	2.6	15980	4.9	12530
July	4.2	-	2100	597	460	92	19	440	300	1.0	13000	3.2	-
Aug	4.2	-	2000	431	440	75	5.5	340	220	2.6	18500	4.0	12000
Sept	4.3	2480	1700	140	410	65	4.6	160	46	3.6	15600	2.4	6490
Oct	4.0	-	2400	-	540	65	120	3690	650	6.2	11810	4.8	24200
Nov	4.2	-	1800	309	500	44	68	1710	300	5.9	6500	3.6	13200
Dec	4.2	3300	2000	420	490	59	27	1400	220	4.3	8200	5.4	13000

Significant neutralizing capacity remains within the dumps. Until this is consumed the acidity of dump drainages is likely to be low. The long term water management strategy assumes that all land dump drainages may become acidic and require some form of mitigation prior to release to the environment.

4.3 Drainage Control

4.3.1 Hydrology of Land Dumps

As outlined in the South Wall Pushback Report (BHP-UTAH, 1988), several drainages discharge from the base of Island Copper land dumps (Figure 2-1), namely: the East Drainage Ditch (EDD) which receives the most acid seep (EMO), the Ten-eighty Ditch (TED) which receives North Dump Drainages (NDD) including all the natural seeps toward the pit and a third drainage which is the old Trey Creek flow (TRC). These three drainages have V-notched weirs and have been monitored with weekly observations over the past year. These data are presented in Table 4-4, 4-5 and 4-6. Figure 4-1 and 4-2 are plots of the flow data for East Drainage Ditch and the Ten-eighty Ditch for October 1989 to August 1990. The plots are similar and echo the precipitation for the same period. On average the flows in the Ten-eighty Ditch represent 62 percent of the north dump runoff with Trey Creek and East Drainage representing 20 and 18 percent, respectively. The estimated total flow from the north dump area based on watershed area, and precipitation records, is 8700 l/min.

At present these drainages are collected in ditches and directed to ponds on the shoreline of Rupert Inlet. A new water management system installed over the summer of 1990 will allow the land dump water to be pumped to the concentrator for treatment when the quality of the water does not meet B.C. Ministry of Environment Pollution Control Objectives. The cost of this water handling system is estimated to be $2,060,000.

This control method will be satisfactory while the concentrator is processing ore. However, if non-compliant water exists upon closure, it will require another treatment method.

Table 4-4

East Drainage Ditch (EDD) Flows September 1989 - August 1990

Date	Flow (l/min)	Zinc (mg/l)	Copper (mg/l)	pH	Conductivity (μmhos)
1989					
Sep 01	-	.52	.02	-	-
Sep 07	25	.39	.02	7.6	1860
Sep 12	-	.77	<.01	-	-
Sep 20	28	.68	<.01	6.9	1600
Sep 28	-	.26	.01	-	-
Oct 03	26	.31	.02	7.5	1800
Oct 11	257	.61	.01	7.7	1600
Oct 16	140	.65	.01	7.4	1700
Oct 17	761	1.03	.02	6.6	1300
Oct 18	2990	8.53	1.18	6.6	1300
Oct 23	3746	5.01	0.66	4.7	1600
Oct 30	916	3.32	0.31	6.0	1300
Nov 06	1760	3.79	0.52	5.1	1400
Nov 09	est 7570 *	-	-	-	-
Nov 14	est 1502	4.36	0.55	4.9	1300
Nov 20	est 1500	3.80	0.46	4.9	1300
Nov 27	est 600	3.85	0.43	4.8	1300
Dec 04	est 3000	4.07	0.60	4.5	1400
Dec 15	est 650	-	-	-	-
Dec 18	est 210	3.41	0.31	4.5	-
1990					
Jan 03	est 1000	4.27	0.55	4.6	1200
Jan 08	est 3500	3.70	0.55	4.4	1200
Jan 16	est 1500	4.1	0.51	4.6	1100
Jan 23	est 1500	5.0	0.56	4.5	1200
Jan 29	est 2400	4.7	0.68	4.4	1400
Feb 05	4277	4.1	0.68	4.5	1200
Feb 13	1779	3.9	0.64	4.6	1100
Feb 20	760	4.4	0.56	4.4	1000
Feb 26	760	4.7	0.63	4.2	1200

* Weir washed out - est from EMO flow.

Table 4-4 (cont'd)

East Drainage Ditch (EDD) Flows
September 1989 - August 1990

Date	Flow (l/min)	Zinc (mg/l)	Copper (mg/l)	pH	Conductivity (μmhos)
1990					
Mar 05	371	4.5	0.50	4.4	1200
Mar 14	760	6.1	0.76	4.3	1500
Mar 22	350	-	-	4.4	1800
Mar 27	470	6.8	0.87	4.2	1400
Apr 02	276	6.5	0.79	4.3	2000
Apr 12	136	6.9	0.79	4.4	2100
Apr 16	132	7.1	0.76	4.2	2200
Apr 25	167	5.8	0.66	4.4	2200
May 07	367	6.6	0.67	4.4	2200
May 16	197	7.9	0.67	4.4	2600
May 22	136	8.1	0.60	4.2	2300
May 29	64	8.7	0.51	4.2	2600
Jun 04	132	5.2	0.33	4.3	2200
Jun 12	280	4.5	0.26	4.3	1900
Jun 20	83	5.9	0.29	4.4	2000
Jul 03	201	3.6	0.14	4.5	2000
Jul 09	64	4.1	0.16	4.5	2100
Jul 16	49	6.1	0.22	4.3	2400
Jul 23	36	7.7	0.27	4.2	2500
Aug 01	15	7.8	0.27	4.2	2250
Aug 08	25	5.5	0.19	4.2	2150
Aug 13	11	6.4	0.23	4.2	2150
Aug 20	49	28	0.92	4.4	1950
Aug 27	19	3.9	0.13	4.4	1950

* Weir washed out - est from EMO flow.

Table 4-5

Ten-eighty Ditch (TED) Flows
October 1989 - August 1990

Date	Flow (l/min)	Zinc (mg/l)	Copper (mg/l)	pH	Conductivity (μmhos)
1989					
Oct 03	4.9	0.010	<0.01	7.8	1000
Oct 11	606	0.41	0.01	7.1	830
Oct 16	416	0.48	0.13	7.7	1100
Oct 17	3028	1.34	0.14	6.5	1700
Oct 18	3407	2.84	0.04	4.7	980
Oct 23	est 11355	3.42	0.19	6.8	1100
Oct 30	4277	2.16	0.20	7.6	930
Nov 06	5299	2.02	0.13	7.4	950
Nov 09	Weir	1.75	0.12	7.2	840
Nov 14	Repair	2.14	0.11	7.5	810
Nov 20	|	1.94	0.08	7.8	880
Nov 27	↓	1.80	0.07	7.8	850
Dec 04	9463	1.58	0.07	7.5	890
Dec 15	3785	-	-	-	-
Dec 18	4165	0.99	0.04	7.8	-
1990					
Jan 03	4731	1.80	0.09	7.5	770
Jan 08	9841	3.1	0.140	7.1	910
Jan 16	6699	1.6	0.72	7.7	-
Jan 23	6321	1.6	0.08	7.6	740
Jan 29	9765	2.7	0.12	7.5	800
Feb 05	11847	5.0	0.10	8.1	720
Feb 13	4353	5.2	0.070	7.5	630
Feb 20	4921	1.2	0.040	7.9	480
Feb 26	4353	1.4	0.075	7.8	750

Table 4-5 (cont'd)

Ten-eighty Ditch (TED) Flows
October 1989 - August 1990

Date	Flow (l/min)	Zinc (mg/l)	Copper (mg/l)	pH	Conductivity (μmhos)
1990					
Mar 05	3312	1.3	0.052	7.9	810
Mar 14	2933	1.2	0.036	7.9	860
Mar 22	1987	-	-	8.0	1000
Mar 27	1987	1.2	0.041	8.0	800
Apr 02	1400	0.77	0.026	8.3	1200
Apr 12	791	0.67	0.015	8.4	1200
Apr 16	693	0.52	0.020	8.2	1300
Apr 25	689	0.53	0.020	8.0	1200
May 07	1022	0.46	0.010	8.1	1200
May 16	893	0.65	0.015	8.0	1200
May 22	693	0.43	0.015	8.2	1200
May 29	401	0.24	0.010	8.1	1300
Jun 04	450	0.19	<0.010	8.0	1000
Jun 12	625	0.20	0.036	7.9	1000
Jun 20	541	0.28	0.020	8.0	1000
Jul 03	454	0.08	<0.010	8.0	1000
Jul 09	322	0.09	<0.010	8.0	1100
Jul 16	322	0.05	0.010	7.8	1200
Jul 23	201	0.04	0.020	7.8	1200
Aug 01	132	0.04	0.021	7.8	1100
Aug 08	83	0.02	0.021	7.7	1150
Aug 13	83	0.03	0.010	7.8	1100
Aug 20	83	0.03	0.010	7.7	1050
Aug 27	64	0.02	<0.010	7.7	1100

Table 4-6

Old Trey Creek (TRC) Flows
October 1989 - August 1990

Date	Flow (l/min)	Zinc (mg/l)	Copper (mg/l)	pH	Conductivity (µmhos)
1989					
Oct 03	est 25	0.18	0.010	8.0	2100
Oct 11	est 25	0.21	0.010	8.1	1800
Oct 16	est 25	0.31	0.051	8.1	1800
Oct 17	est 25	0.31	0.020	7.5	3100
Oct 18	106	1.46	0.051	8.0	1300
Oct 23	1022	2.85	0.070	7.3	1400
Oct 30	435	2.49	0.036	7.9	1600
Nov 06	1363	4.04	0.051	7.6	1900
Nov 09	7570	3.62	0.088	6.9	1200
Nov 14	1930	8.08	0.066	7.3	2000
Nov 20	1514	5.06	0.042	7.7	1900
Nov 27	1098	4.83	0.040	7.8	1900
Dec 04	2952	4.65	0.072	7.4	1500
Dec 15	625	-	-	-	-
Dec 18	530	3.74	0.031	7.8	-
1990					
Jan 03	1173	4.02	0.052	7.7	1700
Jan 08	3634	6.20	0.120	6.8	1800
Jan 16	1665	4.60	0.062	7.4	1700
Jan 23	1968	3.50	0.068	7.2	1400
Jan 29	2460	5.40	0.072	7.4	1700
Feb 05	3596	1.80	0.094	7.6	1600
Feb 13	1741	5.20	0.070	7.7	1700
Feb 20	1022	3.60	0.040	7.8	1800
Feb 26	871	3.70	0.030	7.7	1850

Table 4-6 (cont'd)

Old Trey Creek (TRC) Flows
October 1989 - August 1990

Date	Flow (l/min)	Zinc (mg/l)	Copper (mg/l)	pH	Conductivity (μmhos)
1990					
Mar 05	530	3.00	0.040	8.1	2100
Mar 14	625	2.50	0.036	8.0	1900
Mar 22	348	-	-	7.9	2000
Mar 27	272	2.20	0.030	8.0	1900
Apr 02	273	1.90	0.037	8.1	2700
Apr 12	272	1.50	0.020	8.2	2500
Apr 16	208	1.37	0.025	8.1	2700
Apr 25	208	1.20	0.020	8.0	2700
May 07	397	1.20	0.020	7.9	2200
May 16	189	1.10	0.021	8.0	2700
May 22	212	1.00	0.025	8.1	2600
May 29	159	0.90	0.015	8.0	2800
Jun 04	159	0.94	0.021	7.9	2600
Jun 12	208	0.94	0.031	7.8	1900
Jun 20	114	0.77	0.015	8.0	2200
Jul 03	348	0.65	0.011	8.1	2200
Jul 09	76	0.66	0.010	8.1	2300
Jul 16	238	0.60	0.020	8.0	2500
Jul 23	49	0.52	0.026	8.0	2600
Aug 01	49	0.48	0.026	7.9	2300
Aug 08	61	0.43	0.026	7.8	2400
Aug 13	28	0.57	0.021	7.9	2300
Aug 20	38	0.37	0.020	7.9	2200
Aug 27	28	0.32	<0.010	8.0	2300

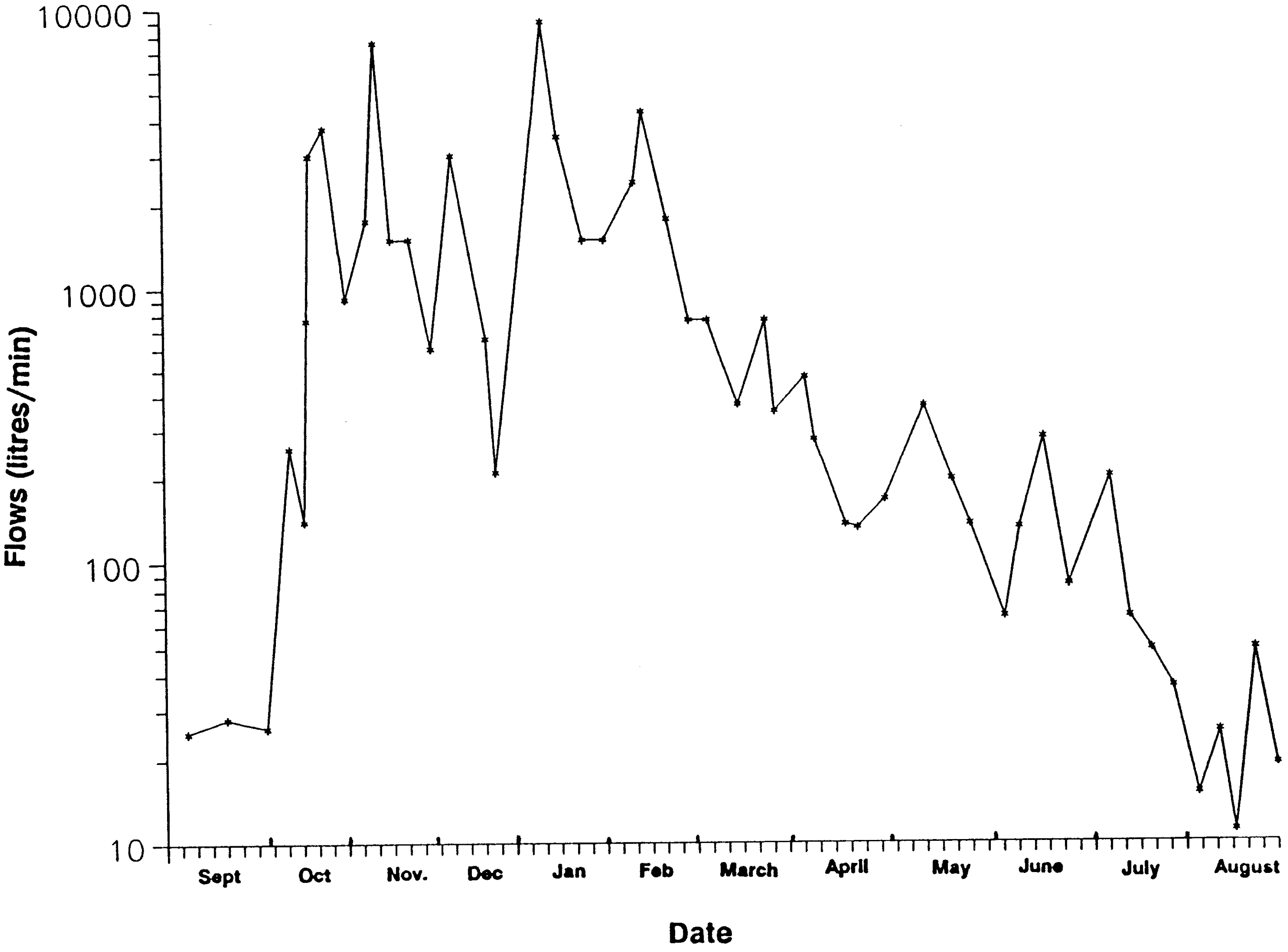


FIGURE 4-1: EAST DRAINAGE DITCH FLOWS

(SEPT 1989-AUG 1990)

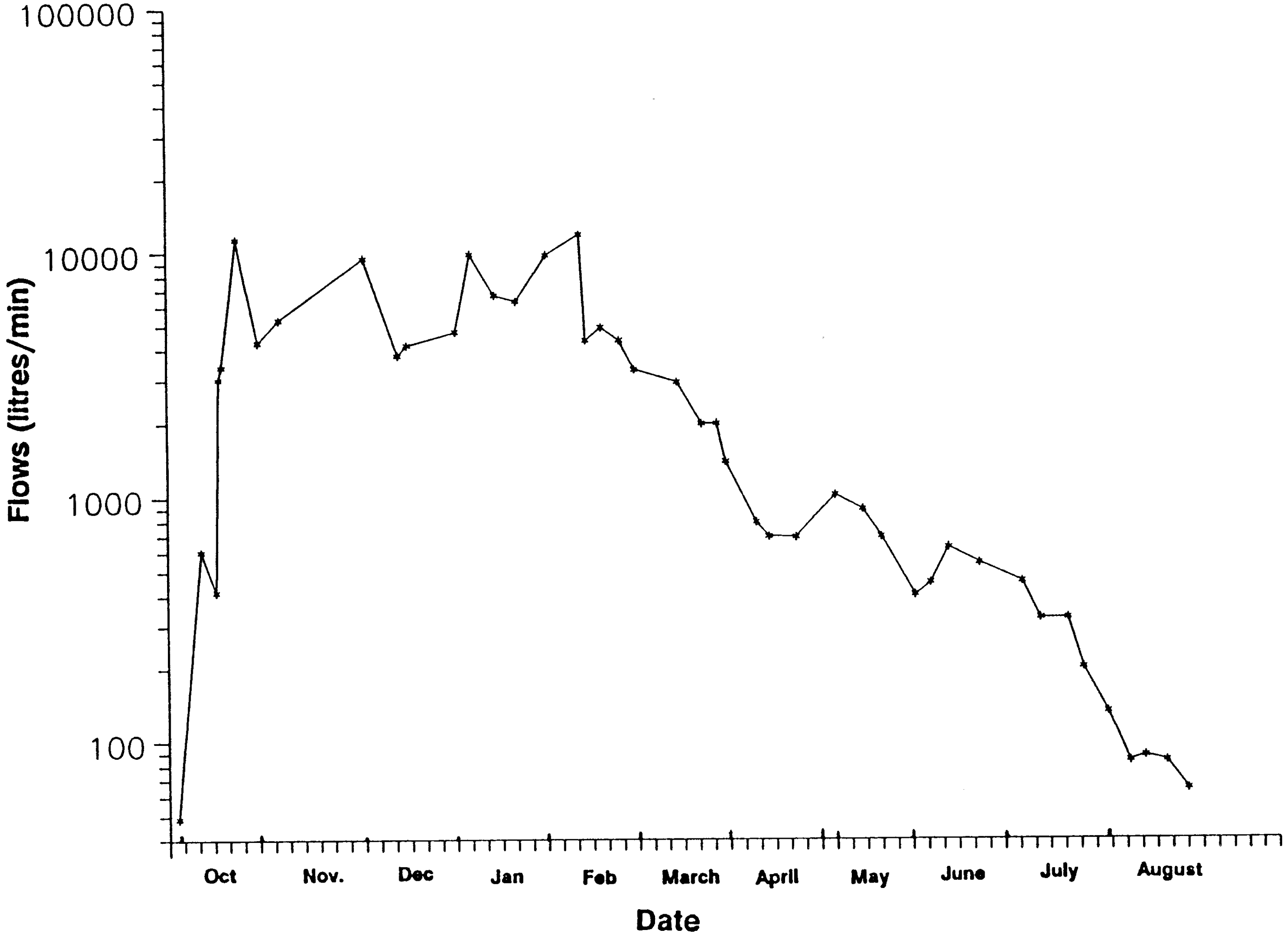


FIGURE 4-2: TEN-EIGHTY DITCH HYDRO GRAPH
(OCT 1989-AUG 1990)

4.4 Closure Treatment of Acid Drainage

The acid drainage at Island Copper is variable with low acidity (<500 mg/l) and occurs only in isolated seeps. The combined drainages still exhibit alkalinity all year long. As a result Island Copper has several options available for treating this runoff.

4.4.1 Passive Treatment

Island Copper's low acidity drainage can lend itself to passive treatment using wetlands (bog) technology. Research in the U.S.A. (Kleinman, Pittsburgh; and Morea, Colorado) using bogs to increase pH and control dissolved heavy metals has been successful in removing 98 percent of the zinc, 99 percent of the copper, 94 percent of the lead, 86 percent of the iron and neutralizing most of the acidity. It is planned to construct a passive wetlands system at Island Copper as an experiment to treat the drainage from land dumps, thus reducing possible long-term active treatment costs.

4.4.2 Active Chemical Treatment

The most common method of treating high acidity drainage is by the use of alkali reactants such as lime. The acidity is neutralized and the heavy metal ions hydrolyzed and precipitated as hydroxides. The primary product of the neutralization reaction is gypsum and most metals precipitate as their respective hydroxides or hydrated metal oxides. The anionic species are precipitated as calcium or metal compounds. The resultant precipitate from the neutralization becomes a water-retaining sludge which requires careful handling to avoid future re-dissolution. The stability of the sludge depends on the environment into which it is placed. Gypsum sludges tend to remain stable if the pH remains above neutral and water movement is reduced to a minimum. Careful selection of disposal sites is hence required to ensure that the metals contained in the sludge are not remobilized.

As a rule the sludge should contain excess alkalinity from treatment and it should be disposed in a location where water in the immediate vicinity is immobilized. Prior to closure a sludge disposal site will be evaluated at the Island Copper Mine in the event it is required and the stability of sludge will be investigated using the best available technology.

4.4.3 Passive In-Pit Treatment

A third option for treatment of acid water is the injection of this water deep into the anoxic zone of the flooded pit using an outfall system. The modelling study has established that such an anoxic zone will exist below 100 metres. A sulfide rich anoxic zone could be used to remove the dissolved metals from the water and allow them to settle to the pit bottom as sediment. If the quality of water draining from the land dumps requires long term treatment this option for treatment should be considered.

4.4.4 Control of Acid Drainage

Research is ongoing to find ways to reduce the amount of acid drainage emanating from the dumps. This could entail encapsulation to eliminate flush water from the dumps as well as measures to reduce the rate of oxidation within the dumps. Such reduction in acid seeps could help assure the success of a passive treatment system for the remaining minimal flows.

5. DUMP EVALUATION

5 - Dump Evaluation

5.0 DUMP EVALUATION

5.1 Rock Dumps

5.1.1 Introduction

Island Copper Mine has been developed as a single open pit, therefore there has been limited opportunity for backfilling. Consequently, most of the overburden material was disposed outside the ultimate pit boundaries. The stripping management plan included four land dumps and one large marine landfill. Approximately eighty-four percent of the material stripped has been deposited in the marine landfill on the shore or underwater in Rupert Inlet.

With the development of acid drainage at the mine site, the company has undertaken an investigation into the disposition of the dumps. Studies have included identification of types of materials in the dumps, their location and quantities. This investigation has been carried out by the University of British Columbia under the direction of Dr. G. Poling and BHP-UTAH Mines Ltd.

5.2 Land Dumps

Four dumps have been developed on land since commencement of operations:

Dump Name	Tonnage (ton x 10^6)	Approximate Area (hectares)
North	84.2	140.8
West	4.6	14.2
South	8.4	14.8
Northwest	1.1	6.8

5.2.1 North Dump

The North Dump is the largest of the four land dumps. The initial deposition of overburden began in April, 1971 and the last in August, 1985. Table 5-1 shows the dump development over the fifteen years.

Table 5-1

North Dump Development 1971 - 1985
Waste Rock and Till
(Tons x 10^6)

Year	Till	Waste Rock	Total	% Till
1971	5.910	1.160	7.070	84
1972	11.726	2.371	14.097	83
1973	2.971	1.921	4.892	61
1974	0.719	2.704	3.423	21
1975	1.395	3.122	4.517	31
1976	2.043	7.152	9.555	34
1977	0.676	0.021	0.697	97
1978	1.219	3.111	4.330	28
1979	1.231	5.829	7.060	17
1980	0.878	3.890	4.768	18
1981	0.456	5.659	6.115	75
1982	0.600	1.305	1.905	46
1983	0.520	4.578	5.098	10
1984	0.051	3.873	3.924	1
1985	0.000	6.766	6.760	0
Total	30.755	53.462	84.217	37

Till material represents 37% of the total quantity deposited. The till is not well mixed with waste rock. The till was deposited principally in the first years of operation when major surface stripping took place. During later years, only rock was placed in the North Dump. This pattern of development resulted in the placement of the bulk of the rock on top of the glacial till. Investigation indicates that the lower low-porosity till layer acts as a passive treatment filter for drainage migrating downward through the dump in those areas where rock overlays the till. Samples collected of West and East Pit rim till are considered to be representative of the tills stripped and placed at lower levels in the North Dump and have an average net neutralizing potential of 38.4 kg $CaCO_3$/tonne.

Acid drainage from the North Dump originates from several regions that have similar characteristics (See Figure 5-1 for locations). These regions are described in the following sections.

5.2.1.1 The Caps

The caps occupy an area of 40 hectares in the center of the North Dump at two levels: the Upper Cap and the Lower Cap (representing between ten and twelve million tons of rock). They average seventeen and nine meters thick, respectively. The caps were constructed from June 1984 to August 1985 with most of the material originating from the west and northwest side of the open pit from elevations 1000 to 1160 feet (Island Copper convention holds that the 1000 foot elevation is mean sea-level).

5.2.1.2 The Eastern Most Outslope (EMO)

EMO is located on the southeastern corner of the North Dump and has two levels: the Upper EMO and the Lower EMO. EMO covers 15 hectares and has an average thickness of 12 meters. There is an estimated 5.5 million tons contained in this area of the North Dump. EMO was built in 1981 and comprises rock with no till base. Most of the material originated from the East 1000 and South East 960 elevations of the pit.

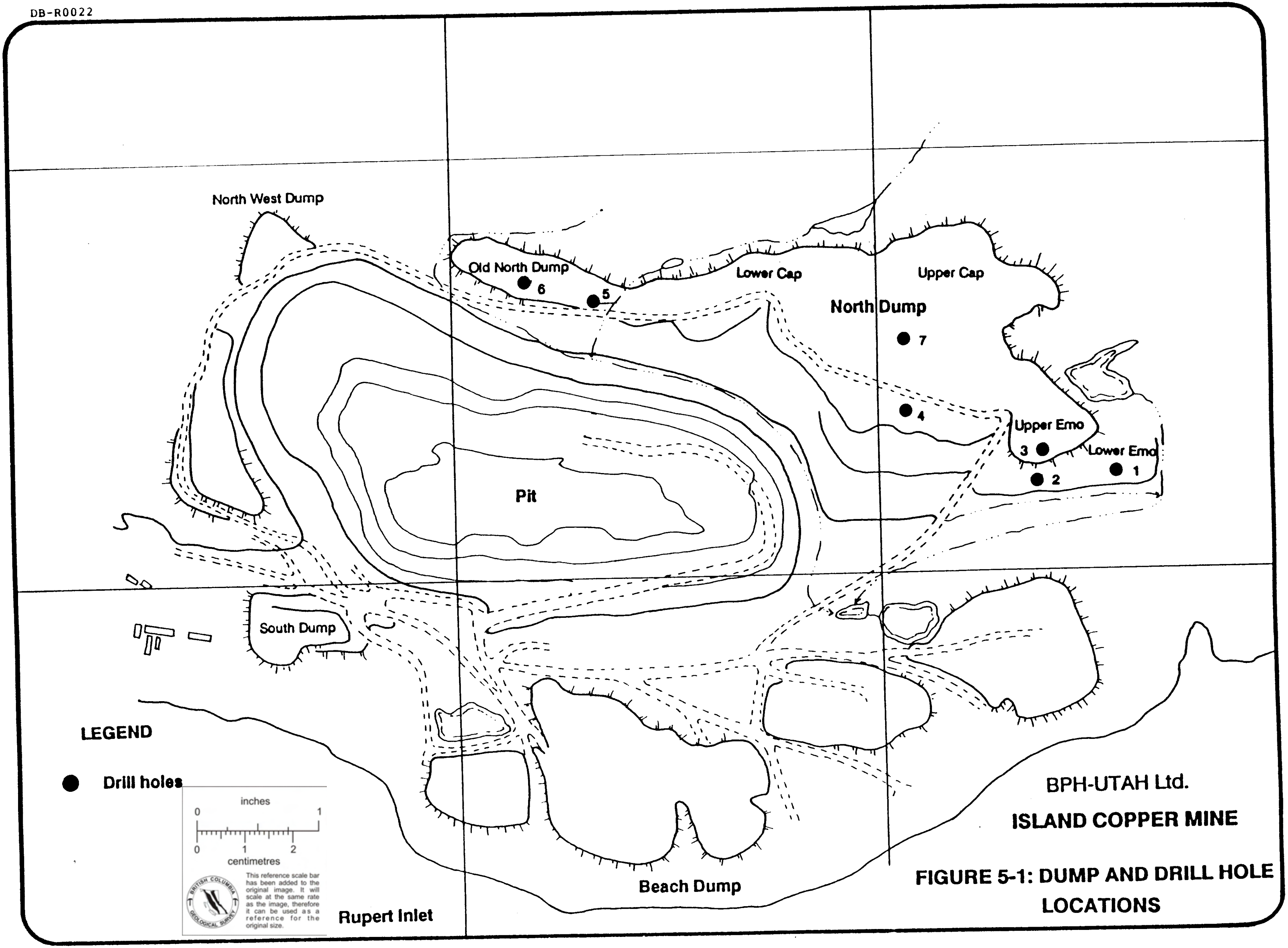
5.2.1.3 The Old North Dump

The old North Dump was built during the period 1972 - 1975 and contains 1.4 million tons of material comprising predominantly till (0.92 million tons), the remainder being rock. Table 5-2 summarizes the North Dump composition.

5.2.1.4 North Dump Drilling Program

To investigate the acid production potential of the North Dump seven vertical holes were percussion drilled using a Becker-505 drill (see Figure 5-1 for location). Holes #1, #2 and #3 were located in EMO area, Hole #4 was located on the lower dump area, Hole #5 was located in the old North Dump area, Hole #6 in the till zone of the old

DB-R0022



This reference scale bar has been added to the original image. It will scale at the same rate as the image, therefore it can be used as a reference for the original size.

BPH-UTAH Ltd.

ISLAND COPPER MINE

FIGURE 5-1: DUMP AND DRILL HOLE LOCATIONS

Table 5-2

North Dump Composition

Area Name	Tonnages (Tons x 10^6)	Material Description
The Caps	12.0	100% Rock, West & Northwest pit
EMO	5.5	100% Rock, East & Southeast pit
Old North Dump	1.4	35% Rock 65% Till
Lower Dump	65.4	51% Rock 49% Till
Total	84.2	

North Dump area, and Hole #7 was selected to pass through the Cap area and into the lower dump. All the holes were 5.58 inches in diameter and 3 inch slotted PVC pipe was used to case each hole. Hole data are presented in Table 5-3.

Table 5-3

Drilling Information for Holes on North Dump April and May 1988

Hole #	Actual Depth (ft)	Calculated Depth
1	70	75
2	46	40
3	32	30
4	102	132.5
5	46	52.5
6	110	120
7	117	124

Notes: The calculated depths are differences in elevation of surfaces before and after dumping.

Solid samples were collected during drilling for acid-base accounting (ABA) evaluation. ABA was determined by measuring the acid producing potential (APP) from total sulfur and the acid consuming potential (ACP) by hot acid titration and calculating the net neutralizing potential (NPP) by subtracting APP from ACP. These ABA data are presented in tabular and graphic format in Table 5-4 and Figure 5-2, respectively. The following observations are made:

- Holes #1 and 2 have negative NNP throughout the entire depth (thus indicating the potential for acid generation) with their average NNP being -28.0 and -53.8 kg H_2SO_4/tonne respectively.
- Hole #3 also has negative NNP except for one interval.
- Hole #4 has slightly negative NNP at the top then is positive at the bottom.
- Hole #5 has varied NNP with one high negative value.
- Hole #6 which is located in tills has a high positive NNP.
- Hole #7 passing through the Cap has a negative value until a depth of 54 feet when it passes into till when the NNP becomes positive.

The drilling data aids characterization of the dump areas. The following is a summary of the acid-base accounting results.

Summary of North Dump Areas

Area Name	Tonnage (Tons x 10^6)	Estimated NNP	Weighted NNP
The Caps	12.0	- 9.2	- 110
EMO	5.5	- 40	- 220
Old North Dump	1.4	+ 10	+ 14
Lower Dump	65.3	+ 22	+1437
Total	84.2		+ 13*

Note: **the results from this ABA should be interpreted with caution as the dump materials are not well mixed.**

* **Overall the North Dump has a positive net neutralizing potential**

Table 5-4

Acid-Base Accounting Results for Samples from Drilling Program on North Dump at ICM

Depth (ft)	APP	ACP	NNP
Hole #1			
0 - 6	38.8	17.3	-21.5
6 -10	32.3	16.3	-16.0
14 -22	46.4	21.7	-24.7
22 -30	51.3	14.5	-36.8
30 -38	36.7	14.7	-22.0
46 -54	53.3	17.5	-35.8
54 -62	53.4	22.7	-30.7
62 -68	40.6	11.2	-29.4
Average	45.4	17.4	-28.0
Hole #2			
0 - 6	14.7	8.1	-6.6
6 -10	15.4	9.3	-6.1
14 -22	86.7	14.0	-72.7
22 -30	93.6	9.1	-84.5
30 -38	83.1	14.0	-69.1
Average	63.9	10.1	-53.8
Hole #3			
0 - 6	62.8	17.3	-45.5
6 -14	41.3	32.8	-8.5
14 -22	25.9	57.5	31.6
22 -30	50.1	30.0	-20.1
Average	45.0	34.4	-10.6
Hole #4			
0 - 6	32.9*	28.3*	-4.6*
6 -14	30.2	26.4	-3.8
14 -22	17.0	8.1	-8.9
22 -30	7.2	4.4	-2.8
30 -38	4.8	3.4	-1.4
38 -46	14.3	11.4	-2.9
46 -54	21.5	9.5	-12.0
54 -62	12.6	12.1	-0.5
62 -70	18.6	23.6	5.0
70 -78	16.1	28.6	12.5
78 -86	12.9	24.6	11.7
86 -94	15.1	28.1	13.0
94 -102	36.2	28.1	-8.1
Average	18.4	18.2	-0.2

Table 5-4 (cont'd)

Depth (ft)	APP	ACP	NNP
Hole #5			
0 - 6	24.4	31.4	7.0
6 -14	32.3	27.6	-4.7
14 -22	57.0	20.6	-36.4
22 -30	24.4	27.5	-6.9
30 -38	17.0	22.9	5.9
38 -46	21.5	30.1	8.6
Average	31.1	26.7	-4.4
Hole #6			
0 - 6	35.3	33.8	-1.5
6 -14	43.0	48.2	5.2
14 -22	20.4	44.6	24.2
22 -30	28.6	41.2	12.6
30 -38	62.7	41.9	-20.8
38 -46	26.9	56.9	30.0
46 -54	21.9	54.0	32.1
54 -62	16.9	49.3	32.1
62 -70	20.1	37.7	17.6
70 -78	-	-	-
78 -86	8.2	19.4	11.2
86 -94	3.9	22.0	18.1
94 -102	3.9	34.6	30.7
102 -110	2.2	13.3	11.1
Average	22.6	38.2	15.6
Hole #7			
0 - 6	33.7	37.0	3.3
6 -14	45.0	36.4	-8.6
14 -22	49.6	41.2	-8.4
22 -30	64.1	43.5	-20.6
30 -38	72.6	51.3	-21.3
38 -46	35.8	62.7	26.9
46 -54	65.2	32.5	-32.7
54 -62	41.6	52.7	11.1
62 -70	35.5	67.1	31.6
70 -78	18.8	55.8	37.0
78 -86	26.9	45.9	19.0
86 -94	26.4	42.5	16.1
94 -102	-	-	-
102 -110	33.5	53.7	20.2
110 -118	23.8	45.1	21.3
118 -126	22.9	25.0	2.1
Average	39.7	46.2	6.5

* Sample was from 3 - 5 feet.

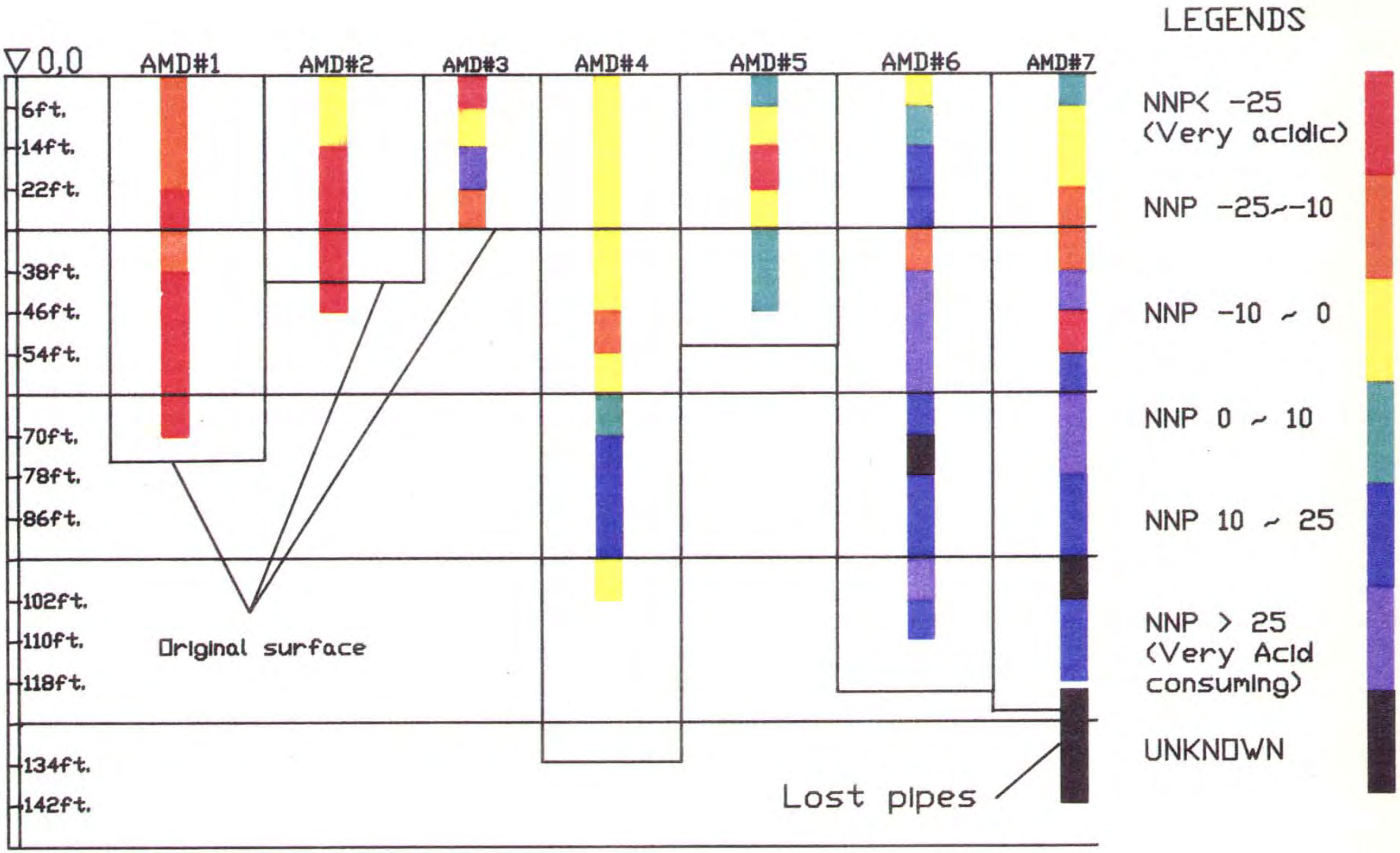


FIGURE 5-2: NET NEUTRALIZATION POTENTIAL OF NORTH DUMP DRILL HOLES

5.2.1.5 North Dump Summary

During the initial years of the North Dump development (1971-1980) 65.3 millions tons of rock and till materials with a positive NNP were deposited in the lower dump area. In the old North Dump area to the northwest and proximal to Twin Lakes, 480,000 tons of rock were covered by 920,000 tons of till (1972-1975). This area is separate from the main dump but is included in the North Dump area. In 1981, the North Dump was extended to the southeast (EMO) with waste rock only (5.5 millions tons). The rock type deposited has a negative NNP (-40). Finally in 1984 and 1985, a lift of rock which has a negative NNP of 9 was placed on the North Dump 9 - 17 meters in depth. From the water quality data collected to date it appears that the EMO area has turned acid and the Cap is turning acid in selected areas. The lower dump is neutralizing acidity passing through it. The Old North Dump area is intermittently generating acid.

5.2.2 West Dump

The West Dump is a small dump located to the west of the pit, and contains 4.6 million tons of rock mined from the western zone of the open pit. During construction of this dump, in 1986-1987, more than 350 samples representing 9.0 million tons of rock were analyzed. Only rock with a NNP greater than -5 was placed on this dump as recommended by Sobek *et al.* (1978) as the minimum NNP to prevent acid generation. Acid generating rock was placed in the ocean. The west drainage dump is now showing indication of being acid.

5.2.3 South Dump

When the South Dump was built in 1988 only material with a positive NNP was placed in it. No drainage has been observed from this dump. It toes into the settling pond and hence is mixed with other drainage sources entering this pond. This dump contains 8.4 million tons of materials.

5.2.4 Northwest Dump

This Dump located to the northwest of the open pit is a small, isolated land dump comprised primarily of rock from the West and Northwest pit zones. The Northwest Dump is presently the subject of a research project funded by BHP-UTAH Mines Ltd.

and the British Columbia Mineral Development Agreement. The purpose of studying this dump is to enhance understanding of dump hydrogeochemistry. The preliminary report is presented in Appendix 2. A summary of the findings are presented below:

- The Northwest dump was constructed in 1982-1984
- It contains 1,052,000 tons
- It covers 5.3 hectares
- It has a bulk density 1847 kg/m3
- 7 drill holes were placed September 1989
- Acid base accounting was conducted at 8 ft. intervals

Mean NNP for Northwest Dump Hole

Hole #	NNP	Hole #	NNP
NWD 1	- 17.3	NWD 7	- 6.7
NWD 2	- 27.8	NWD 8	+ 16.1
NWD 3	- 0.7	NWD 9	- 14.7
NWD 4	+ 54.6		

- With the exception of two holes, the rock is a net acid producer.
- Monitoring of dump CO_2 and O_2 gas contents demonstrates considerable variation.
- No water table evident in the dump.

5.3 Marine Dump

The majority of Island Copper stripping hauled from the open pit has been placed on a marine landfill along the north shore of Rupert Inlet. Prior to 1981 both rock and tills were deposited on the dump. Since 1980 the majority of the material deposited has been rock because glacial tills have been stockpiled for later use in reclamation activities.

There have been 485 x 10^6 tonnes of rock and till deposited as of December, 1989 creating 243 hectares of land. There are approximately 80 x 10^6 tonnes to be deposited during the remaining mine life that will create a final area of approximately 300 hectares.

As required by the Ministry of Energy, Mines and Petroleum Resources Section 6 Approval for the South Wall Pushback, all rock is now placed on the beach dump below or as close as practical to sea level. This disposal strategy is designed to reduce the potential for sulfide oxidation as most of the dump will be submerged.

As part of the study of dump composition, ten drill holes were placed into the beach dump. Solid drill samples have been analyzed for acid-base accounting purposes. Drill hole locations are presented in Figure 5-3 and a summary of the results is presented in Table 5-5.

All rock samples from holes have a net acid producing potential. In addition to the analysis of the solid material recovered from the drilling program the holes have been cased for collection of samples for water quality determinations and dump hydrology investigation.

5.3.1 Marine Dump Hydrology

The beach dump has an estimated hydraulic conductivity of 1 cm/sec. The water table in the dump is at sea level, rising and falling with the tide. The hydraulic gradient or water surface slope is difficult to estimate due to this continuous tidal shift. Calculations indicate the flow velocity to be between 252 and 1135 meters/year in a seaward direction. The average vertical tidal movement is 2.8 meters. This twice daily movement of water into and out of the dump flushes the leading edge of the dump approximately 26 meters into the face. In addition, freshwater from rain or runoff passes through the dump. Compared to the seawater flushing (7.18×10^6 m^3 per exchange) the daily average rainfall is only 0.2% by volume.

5.3.2 Marine Dump Water Quality

Water quality samples have been collected from the beach dump at several depths in each of the ten drill holes placed in the dump. The results of monthly samples collected since the holes were drilled in September 1989 are tabulated in Appendix 3.

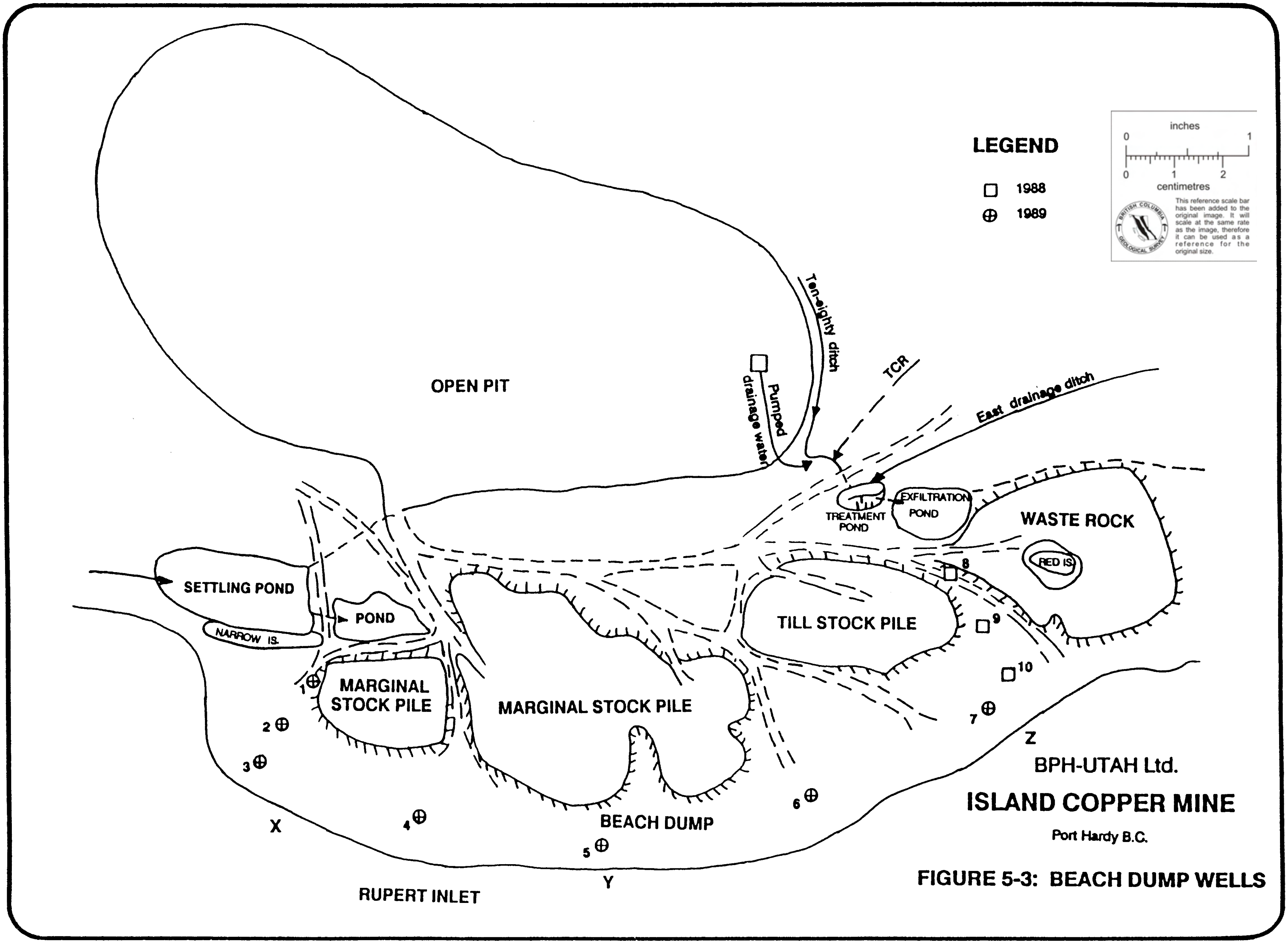


FIGURE 5-3: BEACH DUMP WELLS

Table 5-5

Beach Hole Summary Data

					Above Sea Level			
Hole #	Mean % Sulfur	Mean APP	Mean ACP	Mean NNP	% Sulfur	APP	ACP	NNP
1	1.7	50.1	32.2	-18.1	1.9	57.4	22.5	-35.0
2	1.5	48.1	23.5	-27.4	2.3	71.6	25.1	-46.6
3	2.9	87.5	35.8	-47.0	2.9	89.6	40.8	-48.8
4	1.6	43.6	27.8	-15.7	1.2	37.2	25.2	-11.9
5	3.2	92.5	34.4	-63.3	*1.3	41.0	34.0	-7.0
6	2.8	85.1	37.4	-47.7	2.8	84.2	28.4	-55.0
7	3.3	99.9	31.5	-68.4	3.7	113.7	32.6	-81.1
8	1.6	49.7	37.6	-12.0	1.4	43.7	54.2	+10.5
9	2.3	70.2	44.4	-30.1	1.9	58.9	22.9	-36.0
10	2.3	71.2	42.6	-27.1	2.1	64.2	54.3	-9.9
Mean	2.3	69.8	34.7	-35.7	2.2	66.2	34.0	-32.2

APP, ACP and NNP are expressed in Kg H2SO4/Tonne.

* **Hole #5 had a very high surface value for sulfur, so it was not included in calculating the above sea level mean.**

The water quality data indicate that a significant portion of the water within the dump is saline. The dissolved metals contained within the dump water are precipitated through sulphate reduction in certain zones of the dump during periods of low precipitation, however, the main factor in reducing dissolved metals appears to be dilution of metal-bearing water by Rupert Inlet sea water.

Dissolved manganese content at depth in most of the holes during much of the year is associated with relatively low oxygen content, reflecting reduction of manganese oxide at low oxidation potential. Dissolved iron shows a generally similar distribution to that of manganese, although the higher than background values are not areally or temporally widespread. In some holes, at lower depths, oxygen is notably depleted (e.g. at and below 20 m depth in holes 1 through 5 in January 1990). Presumably, the low oxygen levels can be equated with development of anoxia within the beach dump.

A review of sulphate and salinity data for the samples collected at 20 m depth from September 1989 through January 1990 confirms that sulphate reduction is occurring under anoxic conditions. The dissolved metal concentrations in the oxygen-depleted waters are relatively low suggesting sulphide precipitation. At several sampling sites there appears to be local inputs of dissolved metal and sulphate-rich water in the surface samples. This could reflect a local area of acid generation.

The concentrations of dissolved copper, cadmium and zinc in the interstitial water of the beach dump are significantly elevated compared to background values. The continuous tidal flushing of the face of the dump, and the slow migration of water toward the face of the dump from within, appear to assure that only low concentrations of dissolved metals escape the dump into Rupert Inlet. To verify this observation, samples have been collected off the face of the dump during ebb tides over the past five years (see Figure 5-3 for location). These results are summarized in Table 5-6. The dissolved copper and zinc concentrations are quite variable; the overall means being 3.9 g/l and 8.8 g/l respectively. It is noted that in calculating these values, sampling took place only during ebb tide when water was draining from the dump.

A 24-hour time study during a large tide was conducted to determine if the concentration at the dump face varied with tidal phase. Table 5-7 and Figure 5-4 present these results. Clearly the zinc concentration decreases as the tide floods and increases as the tide ebbs. This study verifies that sampling during ebb tides yields maximum values for zinc at the face of the dump.

The ongoing monitoring program of metal analyses in seawater throughout the Rupert-Holberg basin over the last nineteen years and particularly at Station A located in Rupert Inlet off the mine site has shown no temporal trend in dissolved copper or zinc. This is clearly shown in Table 5-8 which presents the dissolved metals at Station A from 1977 to 1988. Monitoring of the waters of Rupert Inlet will continue.

Table 5-6

Dissolved Metals in Seawater off Beach Dump
(μg/l)

		Station X (Narrow Isl.)				Station Y (Mid Dump)				Station Z (Red Isl.)			
Year	n	Mean	Min	Max	n	Mean	Min	Max	n	Mean	Min	Max	Grand Mean
Dissolved Zinc													
1985	9	4.4	1.6	9.8	9	3.2	1.8	4.7	8	6.6	2.5	15.5	4.7
1986	9	8.9	2.0	26.0	9	8.0	3.2	21.0	9	29.0	3.7	150.0	15.3
1987	12	4.5	1.3	8.9	12	5.3	0.8	9.5	12	5.7	2.1	8.9	5.2
1988	9	9.7	2.8	32	9	6.5	3.1	10.0	9	7.4	2.0	24.0	7.9
1989	18	9.6	2.9	28	18	10.3	3.0	25.0	18	12.5	2.5	40.0	10.8
Dissolved Copper													
1985	9	4.9	2.2	11.7	9	4.3	2.3	9.3	8	5.7	2.4	10.1	5.0
1986	9	3.2	1.7	4.8	9	3.3	1.8	5.0	9	4.6	2.7	18.0	3.7
1987	12	2.5	1.0	3.7	12	2.1	0.7	4.6	12	2.4	1.1	3.8	2.3
1988	9	5.0	1.6	12.8	9	3.3	2.2	7.6	9	4.5	1.3	8.1	4.3
1989	18	4.5	1.3	9.2	18	3.9	1.6	9.7	18	4.3	1.6	14.0	4.2

Table 5-7

24-Hour Time Study of Dissolved Zinc off Beach Dump

Time April 26/90	Tide Height (Meter)	Dissolved Zinc (μg/l)
9	0.1	12.3
11	0.4	10.4
13	2.0	9.9
15	3.2	6.6
17	3.1	6.9
19	2.0	8.7
21	1.4	8.2
23	1.7	7.3
01	3.1	5.2
03	4.0	5.4
05	3.2	4.4
07	1.9	6.2

DB-R0022

ISLAND COPPER MINE

BHP-UTAH Ltd.

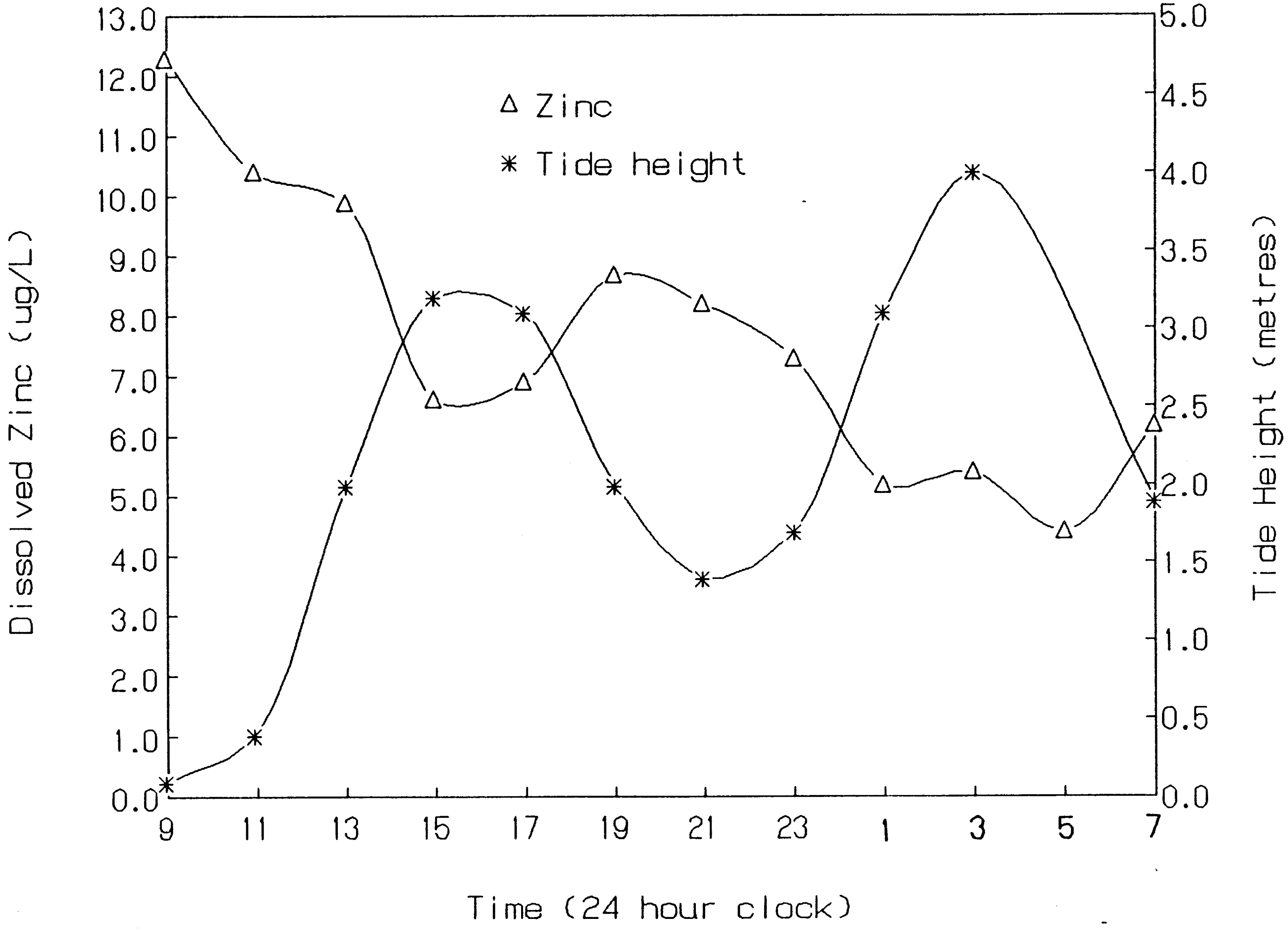


FIGURE 5-4: DISSOLVED ZINC IN SEAWATER AND TIDE HEIGHT DURING 24 HOUR TIME STUDY

Table 5-8

Dissolved Metals in Seawater
MID Rupert Inlet near Mine Site (STN' A)
1977 - 1989
(μg/l)

	Copper		Manganese		Zinc	
Year	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
1977	1.97	0.45	6.30	5.83	-	-
1978	1.77	0.44	6.19	2.80	3.33	1.16
1979	1.83	0.52	4.61	2.64	2.37	1.40
1980	2.40	1.09	6.57	1.97	5.23	4.24
1981	1.88	0.30	7.68	2.53	3.51	2.10
1982	1.94	0.57	5.73	1.79	5.41	2.01
1983	2.40	0.37	4.40	1.46	2.09	0.59
1984	2.49	0.67	4.09	1.21	2.41	1.63
1985	2.32	0.29	2.85	0.87	1.93	0.62
1986	2.08	0.68	3.62	1.18	3.13	2.50
1987	1.62	0.42	3.08	1.08	1.71	0.99
1988	1.93	0.36	3.48	1.23	2.17	1.20
1989	2.84	0.11	5.80	1.49	4.17	1.83

References

REFERENCES

BHP-UTAH Mines Ltd. 1988. South Wall Pushback Description of Project and Related Environmental Issues.

Environment Canada, Atmospheric Environment Service. 1989. Annual Meteorological Summary Port Hardy Airport, B.C.

Graham, R.J. 1963. Determination and Analysis of Numerical Smoothing Weights. NASA Tech. Rep. R-179.

Jacobs, L., S. Emerson and J. Skei. 1985. Partitioning and Transport of Metals Across the Oxygen/Hydrogen Sulphide Interface in a Permanently Anoxic Basin: Framvaren Fjord, Norway. Geochim. Cosmochim Acta 49: 1433-1444.

Johnson, R.D. 1974. Dispersal of Recent Sediments and Mine Tailings in a Shallow-silled Fjord, Ph.D. Thesis, UBC, Vancouver, B.C.

Rescan. 1989. Subaqueous Disposal of Reactive Mine Wastes: An Overview. Prepared for Mine Environment Neutral Drainage (MEND) Program.

Sobek, Andrew A., W.A. Schuller, J.R. Freeman, and R.M. Smith. 1978. Field and Laboratory Methods Applicable to Overburdens and Mine Soils; Environmental Protection Technology Series, U.S.E.P., Springfield, Virginia 22161: 47-55.

APPENDICES

Appendix 1

An Investigation of the Evolution of Water Properties in the Island Copper Mine Following Seawater Flooding

Prepared for

BHP-UTAH Mines Ltd.
Island Copper Mine
P.O. Box 370
Port Hardy, BC V0N 2P0

Prepared by

Donald S. Dunbar, Ph.D.
Sandra L.M. Hodgins, M.A.Sc.

Seaconsult Marine Research Ltd.
820-1200 West 73rd Ave.
Vancouver, BC V6P 6G5

October 1990

EXECUTIVE SUMMARY

One option for abandoning the mine is to flood the pit with seawater through a channel to Rupert Inlet. The present study examines the evolution of the seawater in the pit following such a flooding scheme. It also examines what size of connecting channel is sufficient to provide a fairly uninhibited exchange of water between the pit and the adjacent inlet, while meeting some reasonable navigation criterion. Two mathematical models have been used to investigate these problems; these models are described in the following report. The boundary conditions to drive these models have been derived from water property measurements (mine data) and tidal data from Rupert Inlet.

It has been found that seawater in the pit will evolve to a stratified state with oxygenated water above 5 mg/L in the uppermost 25 m, separated by an anoxic boundary at about 50 m from a lower zone devoid of dissolved oxygen. Periodically, inflows of oxygenated water from Rupert Inlet can be expected to raise DO concentrations below 50 m, and roughly every 15 to 30 years these inflows will reach all the way to the bottom of the pit. These conditions do not appear to be sensitive to the channel depth (over a range of about 4 to 12 m), nor to the time of year that the pit is filled or the assumed values for oxygen uptake coefficients used in the model.

The calculations did reveal rare instances when the DO in the upper layer fell close to zero. These occurrences are caused during some inflow events by the displacement of oxygenated surface waters by anoxic waters from below.

A connecting channel of about 20 ft depth by 200 ft wide appears to be adequate to ensure that the upper layer DO would be maintained above 5 mg/L. Maximum tidal velocities in such a channel would be about 3 knots.

TABLE OF CONTENTS

Page

Executive Summary i

List of Tables iii

List of Figures iv

1.0 Introduction 1

2.0 Physical Oceanography and Chemistry of the Flooded Pit 3

2.1 Description of the Pit 3
2.2 Physical Oceanography 3
  2.2.1 Vertical Mixing 3
  2.2.2 Tidal Elevations in Rupert Inlet 3
  2.2.3 Water Properties in Rupert Inlet 6
  2.2.4 Exchange of Water Properties With Rupert Inlet 6
  2.2.5 Fresh Water Runoff Into the Pit 6
  2.2.6 Density Currents 11
2.3 Dissolved Oxygen 11
2.4 Expected Evolution of the Flooded Pit 15

3.0 Mine Pit Model Formulation and Solution Methods 17

3.1 Basic Assumptions 17
3.2 Governing Equations 19
  3.2.1 Density 19
  3.2.2 Vertical Diffusion 19
  3.2.3 Surface Reaeration 20
  3.2.4 Oxygen Consumption 20
  3.2.5 Fresh Water Runoff 21
  3.2.6 Density Currents 21
3.3 Boundary Conditions 23
3.4 Initial Conditions 23
3.5 Solution Method 23

4.0 Hydrodynamic Model of the Pit and Channel 25

4.1 Assumptions 25
4.2 Model Formulation 25
4.3 Application of C2D 27
  4.3.1 C2D Set-up Summary 27
  4.3.2 Boundary Conditions 28
4.4 Discussion of Results 28

5.0 Mine Pit Simulations 33

5.1 Initial Runs: Periodic Boundary Conditions 33
5.2 Final Runs: Realistic Boundary Conditions 33

6.0 Conclusions 57

TABLE OF CONTENTS

Page

References 59

Appendix A: Expected Chemical Evolution and Oxygen Balances in the Water Column of the Flooded Pit at Island Copper

Appendix B: A Stochastic Model for Non-periodic Boundary Conditions for the Pit Model

LIST OF TABLES

Table		Page
2.1	Depth, Horizontal Area, Volume and Bottom Area of Benches in the Island Copper Open Pit	4
2.2	Monthly Pit Dewatering Flow and Daily Total Runoff into Pit	10
5.1	Parameter Settings for Pit Model Simulations	34
5.2	Dissolved Oxygen Concentrations (mg/L) for Surface Depletion and Bottom Renewal Events from 200-Year Simulations	53

LIST OF FIGURES

Figure		Page
1.1	Map showing location of the Island Copper open pit mine and adjacent inlets.	2
2..1	Annual cycle of daily tidal elevation changes at Makwazniht tide gauge.	5
2.2	Annual cycle of dissolved oxygen in Rupert Inlet near the location of the Island Copper mine.	7
2.3	Annual cycle of temperature in Rupert Inlet near the location of the Island Copper mine.	8
2.4	Annual cycle of salinity in Rupert Inlet near the location of the Island Copper mine.	9
2.5	Dissolved oxygen concentration and density in Indian Arm.	12
2.6	Dissolved oxygen concentration and density in Saanich Inlet.	13
2.7	Dissolved oxygen concentration and density in Rupert Inlet.	14
3.1	(a) Model representation of open pit mine as a set of 32 stacked layers. (b) Distribution of model parameters for first three layers (9 sublayers).	18
4.1	C2D grid layout of the Island Copper Mine Ultimate Pit.	26
4.2	The tidal boundary condition.	29
4.3	Modelled water levels at various points in the channel and pit for representative neap and spring tides.	30
4.4	Modelled current speeds, aligned with the channel, at selected points in the channel and pit for representative neap and spring tides.	31
5.1	Annual vertical profiles and depth-time surface of dissolved oxygen from simulation 1.	35
5.2	Annual vertical profiles and depth-time surface of dissolved oxygen from simulation 2.	36
5.3	Annual vertical profiles and depth-time surface of dissolved oxygen from simulation 3.	37
5.4	Annual vertical profiles and depth-time surface of dissolved oxygen from simulation 4.	38
5.5	Annual vertical profiles and depth-time surface of dissolved oxygen from simulation 5.	39
5.6	Annual vertical profiles and depth-time surface of dissolved oxygen from simulation 6.	40

LIST OF FIGURES

Figure Page

5.7 Annual vertical profiles and depth-time surface of dissolved oxygen from simulation 7. 41

5.8 Time-series of dissolved oxygen at various depths from 200 year simulation 8. 42

5.9 Time-series of dissolved oxygen at various depths from 200 year simulation 9. 43

5.10 Time-series of dissolved oxygen at various depths from 200 year simulation 10. 44

5.11 Time-series of dissolved oxygen at various depths from 200 year simulation 11. 45

5.12 Time-series of dissolved oxygen at various depths from 200 year simulation 12. 46

5.13 Time-series of dissolved oxygen at various depths from 200 year simulation 13. 47

5.14 Time-series of dissolved oxygen at various depths from 200 year simulation 14. 48

5.15 Time-series of dissolved oxygen at various depths from 200 year simulation 15. 49

5.16 Time-series of dissolved oxygen at various depths from 200 year simulation 16. 50

5.17 Time-series of dissolved oxygen at various depths from 200 year simulation 17. 51

5.18 Daily oxygen concentrations at various depths from the first 14 years of simulation 15. 54

5.19 Renewal/depletion event 1 from 200 year simulation 15 55

5.20 Renewal/depletion event 2 from 200 year simulation 15 56

1.0 INTRODUCTION

The Island Copper open pit mine is located near the northern shore of Rupert Inlet (Fig. 1.1). Production at the mine will cease within the next few years, and a proposal to flood the pit through a permanent connection to Rupert Inlet is being studied. This would result in the creation of an artificial inlet that could support the diversity of life and recreational use found in other inlets along the British Columbia coastline.

Migration of aquatic life from Rupert Inlet into the pit would be expected to occur soon after flooding was completed. There is interest, therefore, in the potential of the pit to sustain permanent colonies of marine organisms and to support recreational activities. Thus, prior to flooding the pit, it is essential to estimate the distribution and evolution of critical water properties. Of foremost importance is the concentration of dissolved oxygen which is crucial to the establishment and maintenance of a healthy ecosystem in the new inlet. It, in turn, depends on the tidal exchange of water with Rupert Inlet through the channel combined with the vertical density structure inside the flooded pit, as well as reaeration at the surface.

Accurately forecasting the evolution of the new inlet is difficult, owing to the complex interaction of physical and chemical processes that would take place, including mixing due to wind and tidal currents, seasonal and interannual variability of source waters in Rupert Inlet, episodic intrusions of dense water, and variable rates of precipitation and resulting run-off into the inlet. Added to this uncertainty are the poorly known rates of oxygen production and consumption that would arise due to the establishment of life in the flooded pit.

Useful estimates can be obtained, however, by employing a numerical model to calculate the temporal and vertical changes in water properties in the pit given initial vertical distributions and time-series of boundary values at the connection to Rupert Inlet. A great advantage of such a model is the ability to systematically investigate the effect of changes in channel depth, date of filling, and other key parameters on the subsequent evolution of the pit.

This report presents the results of the first attempt to predict the water properties in the pit after the completion of flooding. A numerical model has been developed and applied to the Island Copper open pit in order to estimate the evolution of dissolved oxygen, salinity, temperature, and density. Physical processes relevant to the long-term evolution of the new inlet have been included in the model.

Chapter 2 describes the physical setting and dimensions of the Island Copper mine together with the chemical and physical oceanographic processes relevant to water quality in the flooded pit. Chapter 3 discusses the formulation of the numerical model used to simulate the long-term evolution of water properties in the flooded pit. The hydrodynamic model used to estimate the volume exchange between Rupert Inlet and the pit is discussed in Chapter 4, while the results of the mine pit model simulations are presented in Chapter 5. Finally, our conclusions and recommendations for further work are contained in Chapters 5 and 6.

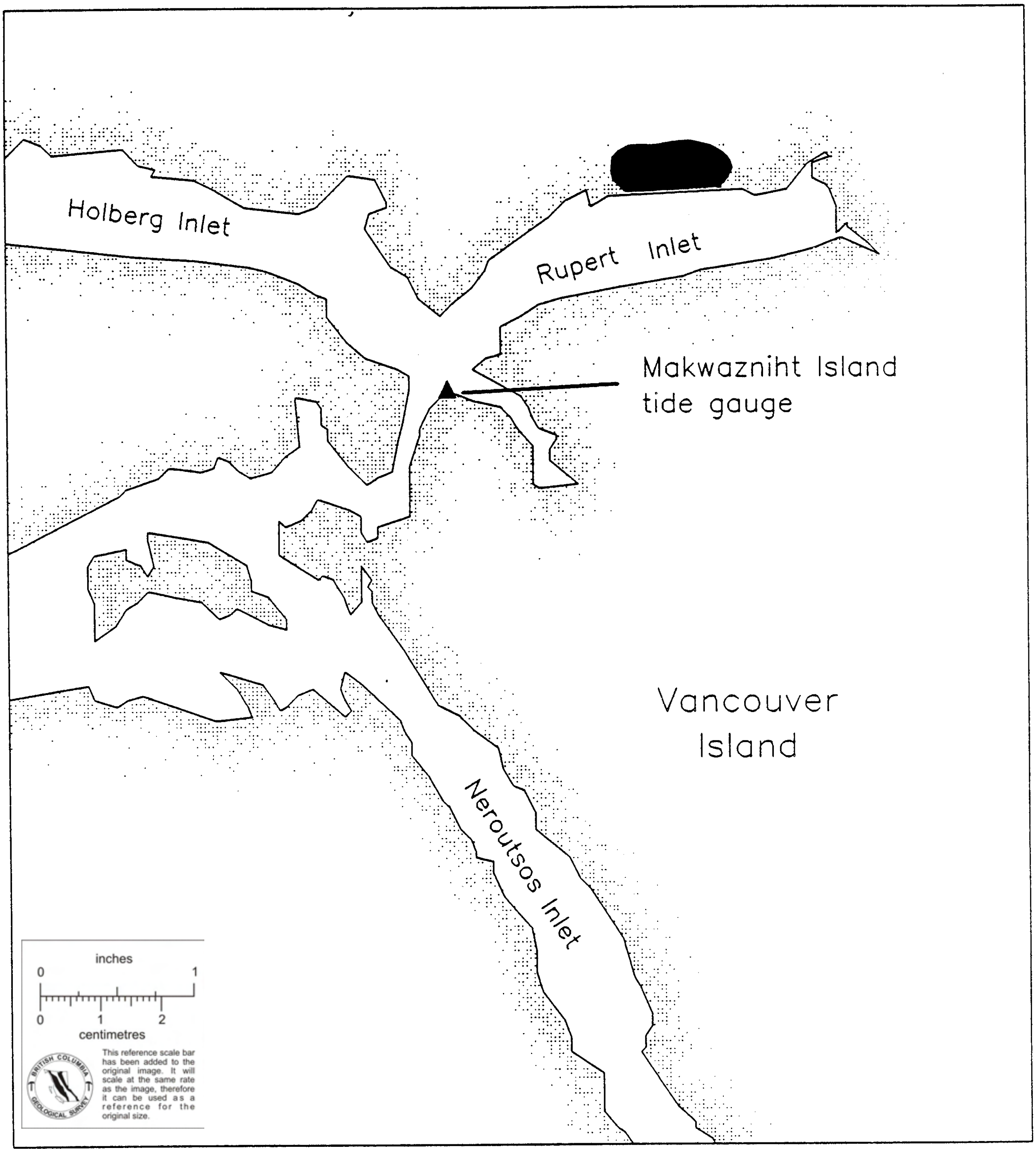


Figure 1.1 Map showing location of the Island Copper open pit mine and adjacent inlets.

2.0 PHYSICAL OCEANOGRAPHY AND CHEMISTRY OF THE FLOODED PIT

2.1 Description of the Pit

The Island Copper open pit is located near the shore of Rupert Inlet on northern Vancouver Island (Fig. 1.1). It is roughly elliptical in shape with a width of 1.05 km and a length of 2.35 km. The general orientation is such that the long axis is nearly parallel to the shoreline. The pit contains 32 horizontal benches spaced 40 feet (12.19 m) apart from the surface down to the maximum depth of 390 m. The side walls of the pit between benches are nearly vertical. The surface area of the pit is 1.67 km^2 and its volume is 0.278 km^3. Table 2.1 lists the depth, horizontal area, volume, and bottom area of each bench. The bottom area corresponds to the horizontal surface that is available for the deposition of sediment, and thus for benthic oxygen uptake.

2.2 Physical Oceanography

2.2.1 Vertical Mixing

Vertical mixing in a typical British Columbia inlet is a complex process associated with the dissipation of turbulent kinetic energy. The principle sources of this energy are tidal currents, shear at the interface of density flows, and surface wind stress. Internal waves may transport energy from a source--usually near the entrance to the inlet--to locations at the sides or bottom, where wave breaking converts the energy to turbulent mixing. The effect of mixing is to transport scalars, such as dissolved oxygen, through the inlet, reducing spatial gradients in the process.

Mixing is a small scale process whose details are often ignored in numerical models of inlets by parameterizing its effects in an analogue to molecular diffusion. In this approach, the diffusion coefficient is calculated as a function of the local stability of the water column. This method has been adopted in the development of the open pit model (Section 3.2.2).

2.2.2 Tidal Elevations in Rupert Inlet

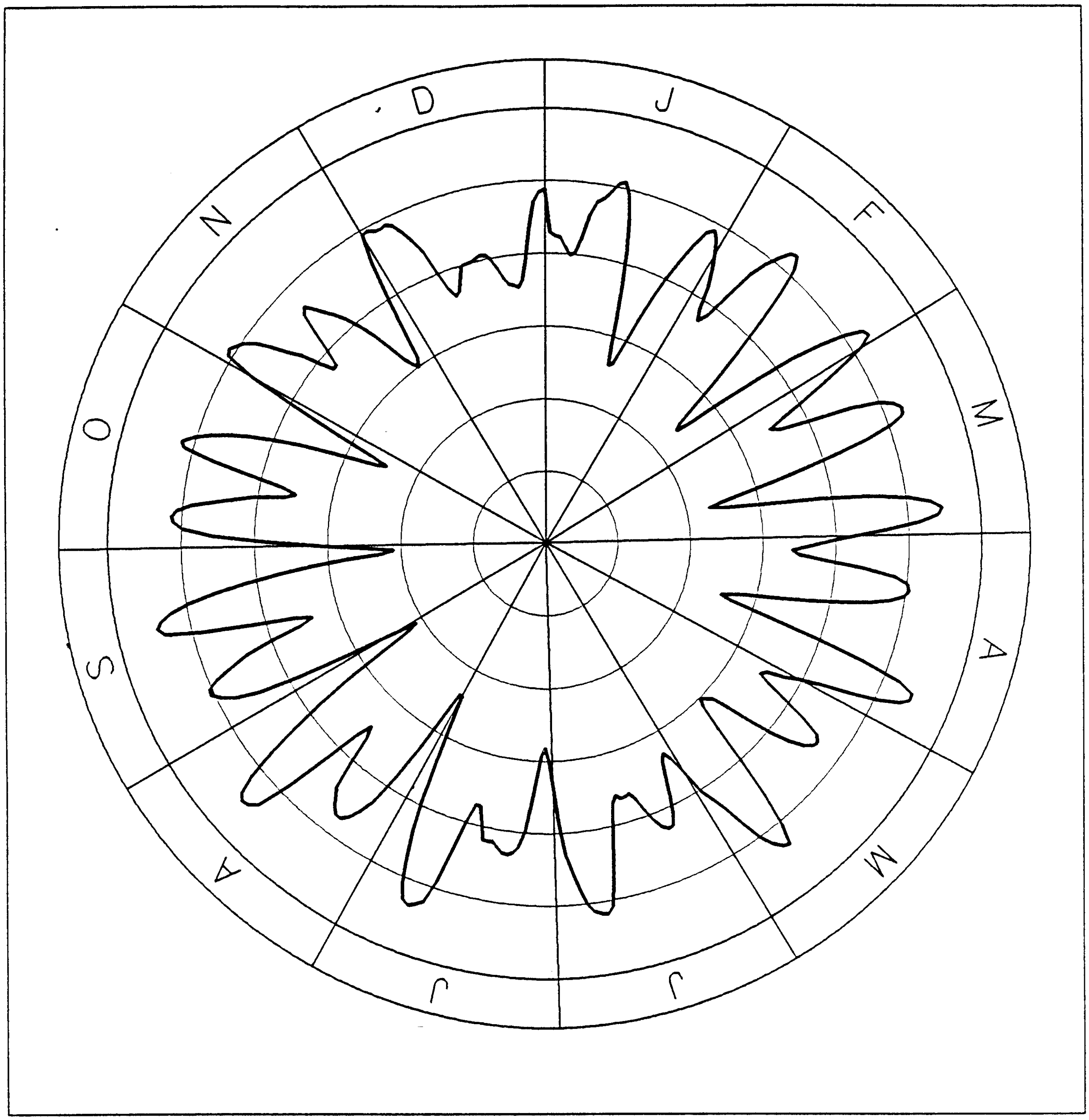
The periodic ebb and flood of the astronomical tide corresponding to changes in water level at the entrance to the flooded pit would result in the exchange of water properties with Rupert Inlet, and provide the main source of energy for turbulent mixing. The volume of exchanged water has been calculated from the total positive change in surface level during each day of a calendar year. The product of these values and the surface area of the pit yields the tidal prism for each day, and represents the daily volume of water flowing into and out of the pit provided there is no significant dissipation of energy in the connecting channel.

A one year time-series of quarter-hourly elevations was calculated from the tabulated harmonic constants for a tide gauge at Makwazniht Island (Fig. 1.1). All positive differences between consecutive elevations were added together during each of the 365 days in the synthesized record (Fig. 2.1).

Table 2.1

Depth, Horizontal Area, Volume and Bottom Area of Benches in the Island Copper Open Pit

Bench	Depth ft	Depth m	Area ft^2	Area m^2	Volume ft^3	Volume m^3	Bottom Area ft^2	Bottom Area m^2
1	40	12	17,965,600	1,669,059	718,624,000	20,349,166	759,202	70,532
2	80	24	17,206,398	1,598,527	688,255,900	19,489,237	852,305	79,182
3	120	37	16,354,093	1,519,345	654,163,700	18,523,854	754,303	70,077
4	160	49	15,599,790	1,449,268	623,991,600	17,669,475	675,420	62,749
5	200	61	14,924,370	1,386,519	596,974,800	16,904,444	700,397	65,069
6	240	73	14,223,973	1,321,450	568,958,900	16,111,122	648,050	60,205
7	280	85	13,575,923	1,261,245	543,036,900	15,377,093	671,178	62,355
8	320	98	12,904,745	1,198,890	516,189,800	14,616,868	604,870	56,194
9	360	110	12,299,875	1,142,696	491,995,000	13,931,747	681,127	63,279
10	400	122	11,618,748	1,079,417	464,749,900	13,160,252	737,785	68,542
11	440	134	10,880,963	1,010,875	435,238,500	12,324,582	902,730	83,867
12	480	146	9,978,233	927,008	399,129,300	11,302,084	837,140	77,773
13	520	158	9,141,093	849,235	365,643,700	10,353,877	827,805	76,905
14	560	171	8,313,288	772,330	332,531,500	9,416,244	635,983	59,085
15	600	183	7,677,305	713,245	307,092,200	8,695,883	668,650	62,120
16	640	195	7,008,655	651,125	280,346,200	7,938,521	489,992	45,521
17	680	207	6,518,663	605,604	260,746,500	7,383,519	625,720	58,132
18	720	219	5,892,943	547,472	235,717,700	6,674,782	503,985	46,821
19	760	232	5,388,958	500,651	215,558,300	6,103,932	519,135	48,230
20	800	244	4,869,823	452,421	194,792,900	5,515,921	379,290	35,237
21	840	256	4,490,533	417,184	179,621,300	5,086,309	655,208	60,871
22	880	268	3,835,325	356,313	153,413,000	4,344,173	423,812	39,373
23	920	280	3,411,513	316,940	136,460,500	3,864,131	521,425	48,442
24	960	293	2,890,088	268,498	115,603,500	3,273,527	574,281	53,352
25	1,000	305	2,315,807	215,146	92,632,270	2,623,054	409,139	38,011
26	1,040	317	1,906,668	177,135	76,266,730	2,159,633	280,843	26,091
27	1,080	329	1,625,825	151,044	65,033,000	1,841,530	434,213	40,340
28	1,120	341	1,191,612	110,704	47,664,490	1,349,708	353,856	32,874
29	1,160	354	837,756	77,830	33,510,250	948,905	295,125	27,418
30	1,200	366	542,631	50,412	21,705,250	614,624	267,775	24,877
31	1,240	378	274,856	25,535	10,994,250	311,323	171,893	15,969
32	1,280	390	102,963	9,566	4,118,500	116,623	102,963	9,566
Total			245,769,016	22,832,689	1,240,825,748	278,376,143	17,965,600	1,669,059



Daily tidal inflow. 1 m ring spacing

Figure 2.1 Annual cycle of daily tidal elevation changes at Makwazniht tide gauge.

2.2.3 Water Properties in Rupert Inlet

Measurements of salinity, temperature, and dissolved oxygen made in Rupert Inlet have been obtained from Utah Mines. These have been used to define representative annual cycles for input to the numerical model. Figures 2.2 to 2.4 show polar plots of salinity, temperature, and dissolved oxygen at the surface and depths of 5, 10, 15, 20 and 30 m. Data for all years have been plotted (open circles) according to the day number in the year.

Periodic smoothing cubic splines (bold lines) were fitted to the data at each depth. A variable smoothing parameter was subjectively tuned to provide representative annual cycles. The continuous curves were then evaluated at daily intervals to provide 365 values for each parameter at each depth. These values provided the boundary data for an initial set of runs. A non-periodic boundary condition was then derived (Appendix B) for a set of realistic long-term simulations.

2.2.4 Exchange of Water Properties With Rupert Inlet

A permanent channel linking Rupert Inlet to the mine has been proposed to provide the means for flooding the pit, and allowing exchange of properties between the two water bodies. The role of tidal currents in providing energy for turbulent mixing in the flooded pit has been discussed in Section 2.2.2. These same currents would be expected to generate strong turbulent mixing within the channel itself, resulting in near homogeneous conditions. Using the daily values discussed in Section 2.2.3, estimates of salinity, temperature and dissolved oxygen in the channel were calculated by integrating the water property data from the surface to the depth of the channel.

The fate of seawater flowing into the flooded pit will depend on its density relative to the vertical density structure in the pit. In the following discussion, it is assumed that the pit will always be stably stratified, that is, the water density will increase monotonically from the surface to the bottom. Under this assumption, two possible situations may arise. In the first case, channel water is denser than pit water down to at least the channel depth. Water will then flow down the sloping side of the pit as a density current (Section 2.2.6), mixing with the in situ waters at, or slightly below, the point of neutral density, or possibly at the pit bottom if the flow is dense enough.

In the second case, channel water is less dense than pit water at a level above the channel depth which may extend to the surface. We then make the reasonable assumption that there will always be sufficient turbulent energy available to mix the channel water with the denser pit water at the same level.

2.2.5 Fresh Water Runoff Into the Pit

Estimates of the monthly fresh water runoff into the pit have been made using values for the pit dewatering flow (Table 2.2), which indicates the mean volume of water pumped from the pit during each month. Based on information obtained from Utah Mines we have assumed that these values represent 50% of the total runoff into the pit. The second column in Table 2.2 has been calculated by doubling the first column and dividing by the number of days in the month. The largest value occurs in December and is equivalent to a single, continuous inflow of 0.34 m^3/s. This is one to three orders of magnitude smaller than typical fresh water runoff

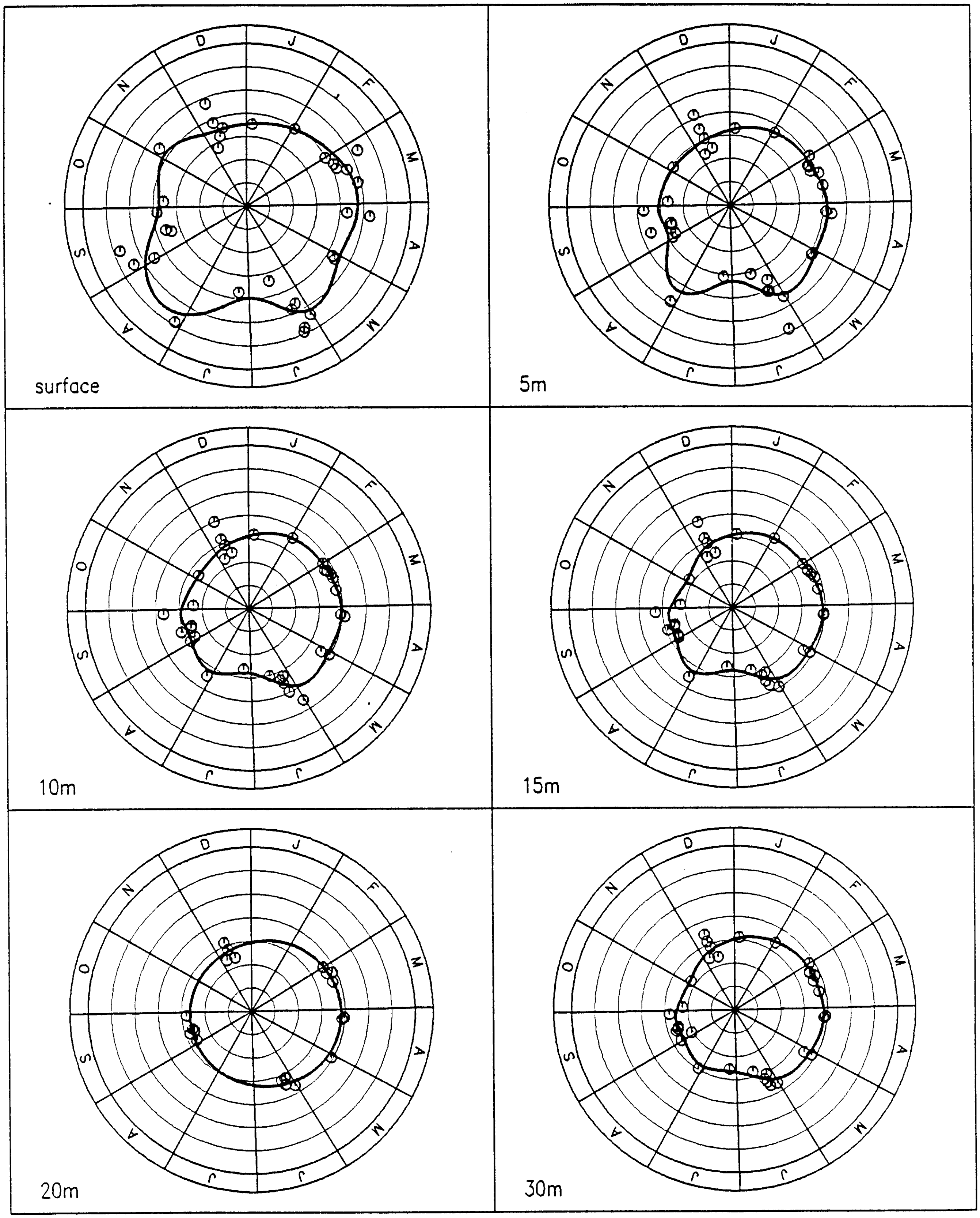


Figure 2.2 Annual cycle of dissolved oxygen in Rupert Inlet near the location of the Island Copper mine

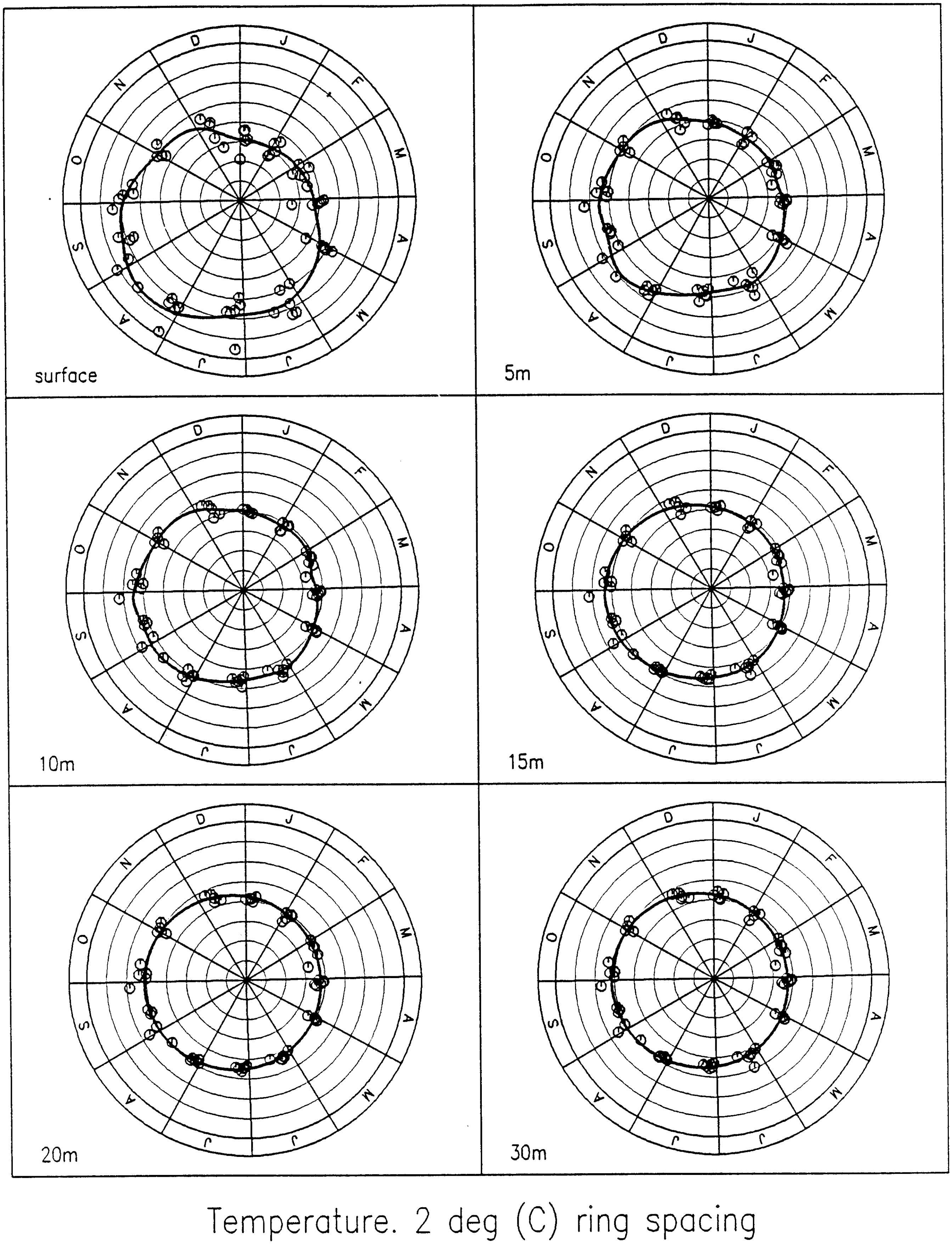
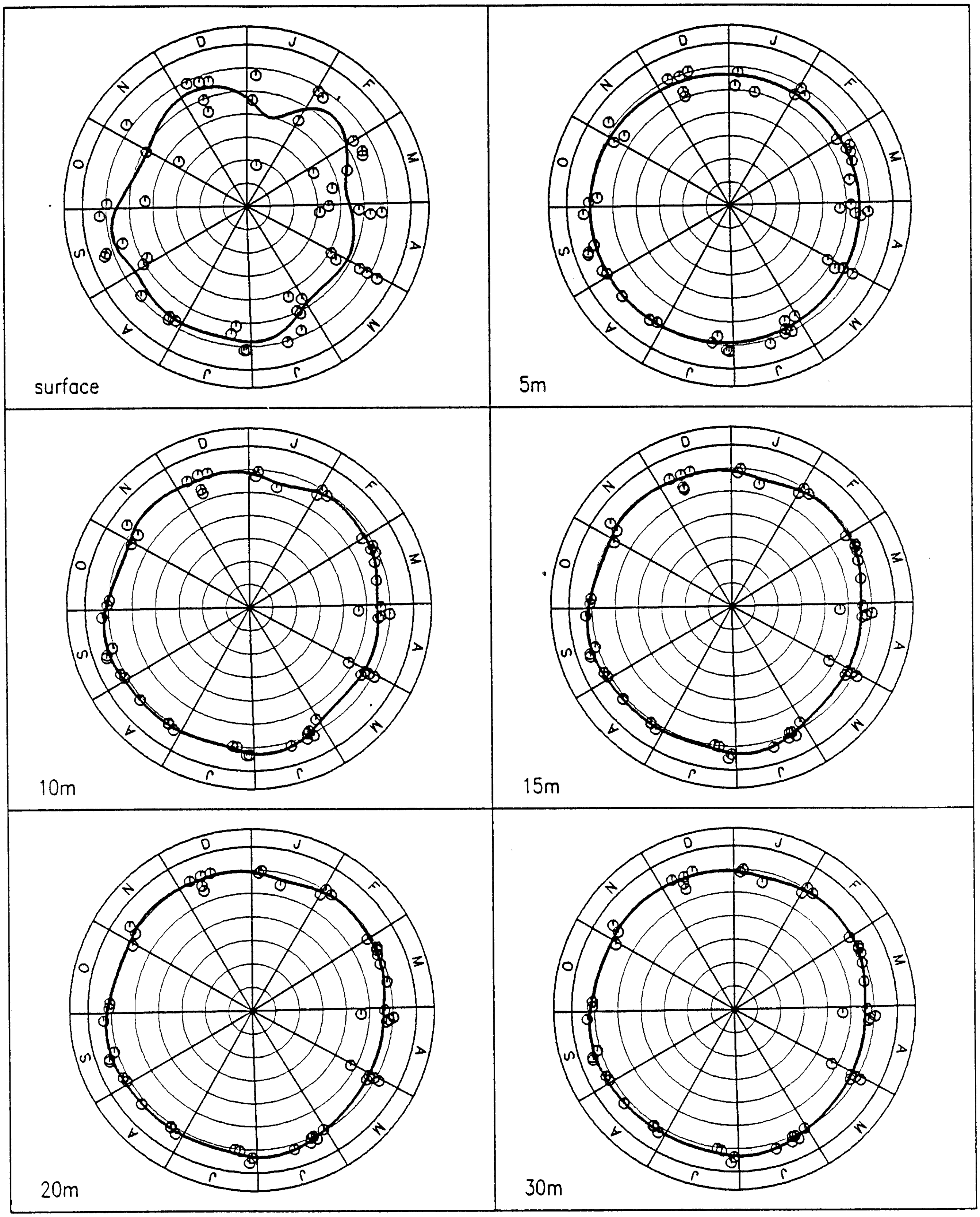


Figure 2.3 Annual cycle of temperature in Rupert Inlet near the location of the Island Copper mine.



Salinity. 5 ppt ring spacing

Figure 2.4 Annual cycle of salinity in Rupert Inlet near the location of the Island Copper mine.

Table 2.2

Monthly Pit Dewatering Flow† and Daily Total Runoff into Pit

Month	Pit Dewatering Flow (m^3/month)	Total Runoff (m^3/day)
Jan	353,716	22,820
Feb	266,836	19,060
Mar	237,373	15,314
Apr	179,955	11,997
May	114,836	7,409
Jun	118,352	7,890
Jul	87,048	5,616
Aug	115,506	7,452
Sep	227,999	15,200
Oct	409,795	26,438
Nov	409,628	27,309
Dec	463,531	29,905

†50% of total runoff

values for inlets in British Columbia. This small volume of fresh water will mix with the surface waters of the pit, reducing its salinity and hence density.

2.2.6 Density Currents

In Section 2.2.4 the possibility of density flows along the sloping sides of the pit was introduced. The acceleration of the flow will be governed by the component of gravity along the slope multiplied by the relative difference in densities, as well as frictional drag along the bottom and at the interface between the stationary pit water and the flow. Current shear at the interface results in turbulent entrainment and mixing of water into the flow, with resulting modification of its properties. Finally, at a level when the velocity of the flow reaches zero or, if the density is large enough, at the bottom of the pit, separation will occur and the flow will leave the slope to interleave and mix with the waters at that depth. As a consequence, water above the intrusion depth is displaced upwards, and a volume of water at the surface equal to the inflow volume will drain from the pit.

2.3 Dissolved Oxygen

The concentration of dissolved oxygen in the pit will strongly depend on the character of the ecosystem that becomes established. Unlike mass and salinity, which are conservative quantities, biological and chemical activity provide sources and sinks for oxygen.

The dissolved oxygen concentration in British Columbia inlets often exhibits a seasonal cycle. Beginning in early spring, biological activity increases as the water warms and light levels increase. Phytoplankton begin multiplying quickly, creating a large mass of organic matter in the upper water column; concurrently, an enhanced oxygen demand is fostered by grazing zooplankton. Bacteria oxidize detritus as it sinks, adding to the oxygen demand below the euphotic zone. As winter approaches, ambient insolation decreases, the water cools and biological activity is suppressed. Oxygen demand decreases, while upwelling along the outer coast provides a source of dense, oxygenated, and nutrient rich water that is advected into the inlets, thereby replenishing the oxygen supply. Maximum oxygen levels occur in late winter or early spring, after which the cycle repeats. Interannual variability modifies the scenario from year to year; suppressing the development of an oxygen maximum in some years, or altering the timing of events.

Figures 2.5 to 2.7 illustrate the annual cycle in three British Columbia inlets--Saanich Inlet, Indian Arm and Rupert Inlet. Each figure presents the dissolved oxygen concentration and density over a five year period at two depths; 50 and 100 m for Saanich Inlet and Indian Arm; and 60 and 105 m for Rupert Inlet. Rupert Inlet has a maximum depth of 150 m, has relatively high runoff, and is in close proximity to the Pacific Ocean. Saanich Inlet and Indian Arm have maximum depths of about 220 m, have smaller than normal supplies of fresh water, and are separated from the Pacific Ocean by Juan de Fuca Strait and the Strait of Georgia. Saanich Inlet is also known to support high levels of biological productivity, and is separated from Satellite channel by a relatively shallow sill (70 m maximum depth) so that anoxic conditions exist at most times near the bottom.

Several general features are common to these inlets. A maximum in the dissolved oxygen concentration occurs between January and the end of April in most years. Oxygen levels then

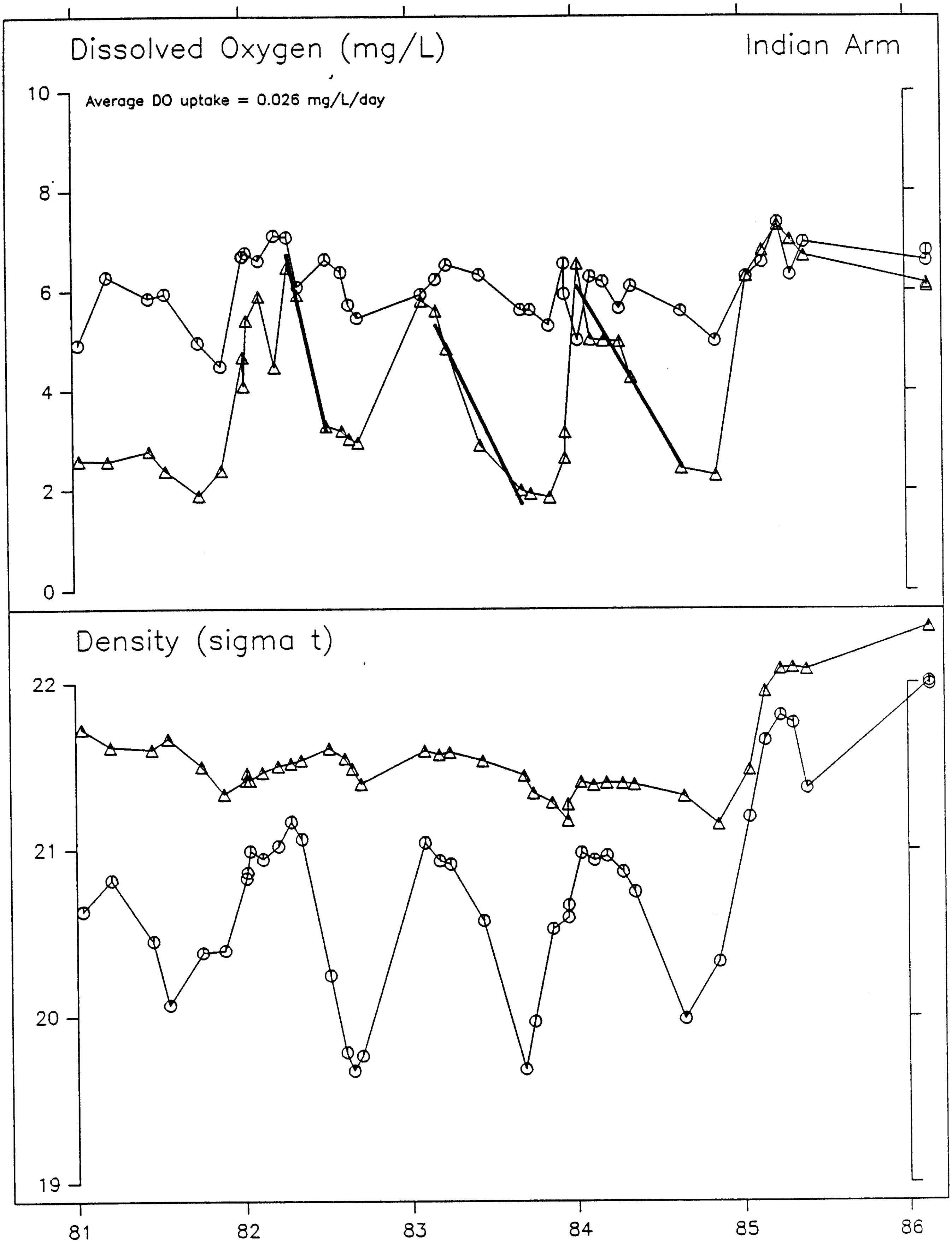


Figure 2.5 Dissolved oxygen concentration and density in Indian Arm (circles - 50 m; triangles - 100 m).

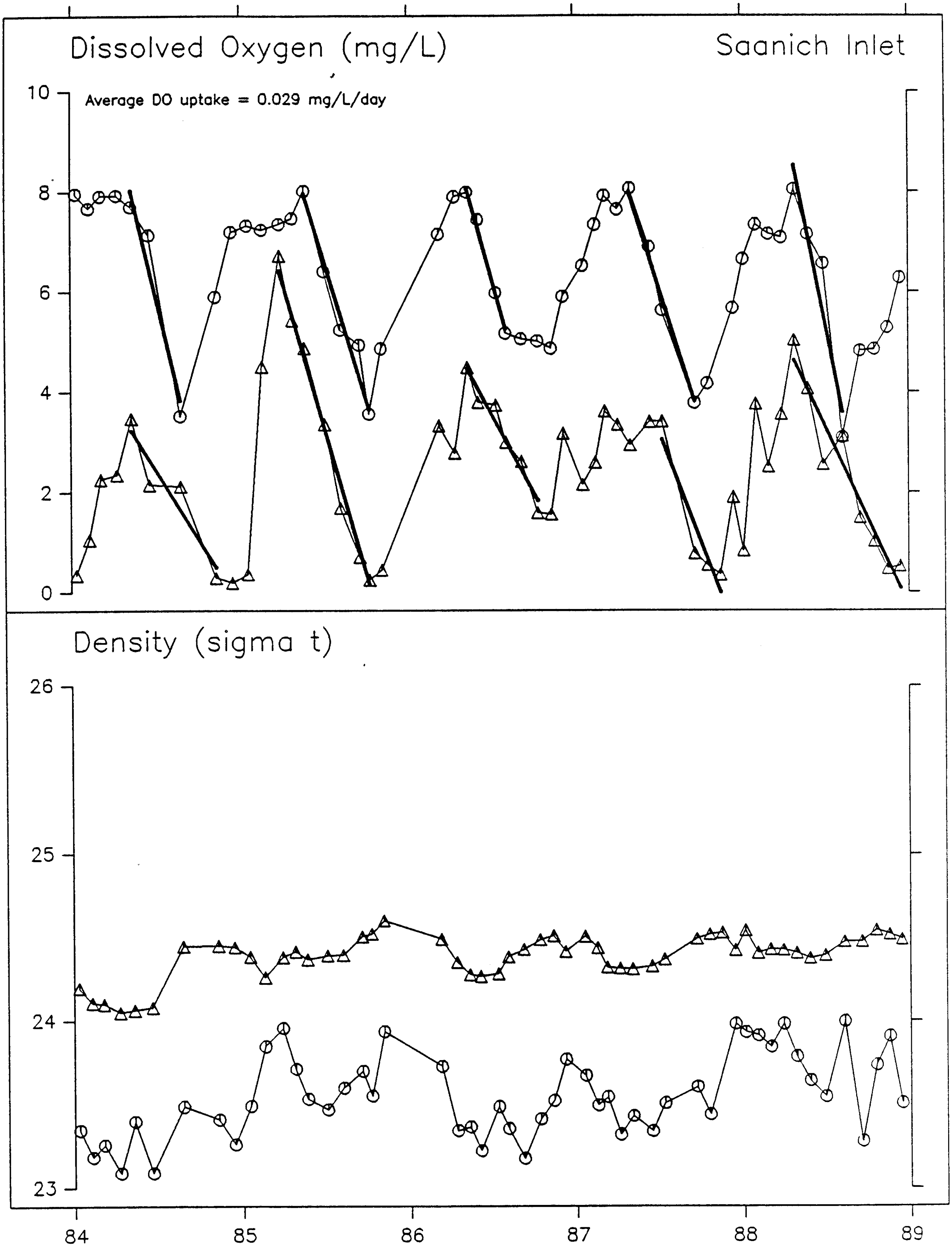


Figure 2.6 Dissolved oxygen concentration and density in Saanich Inlet (circles - 50 m; triangles - 100 m).

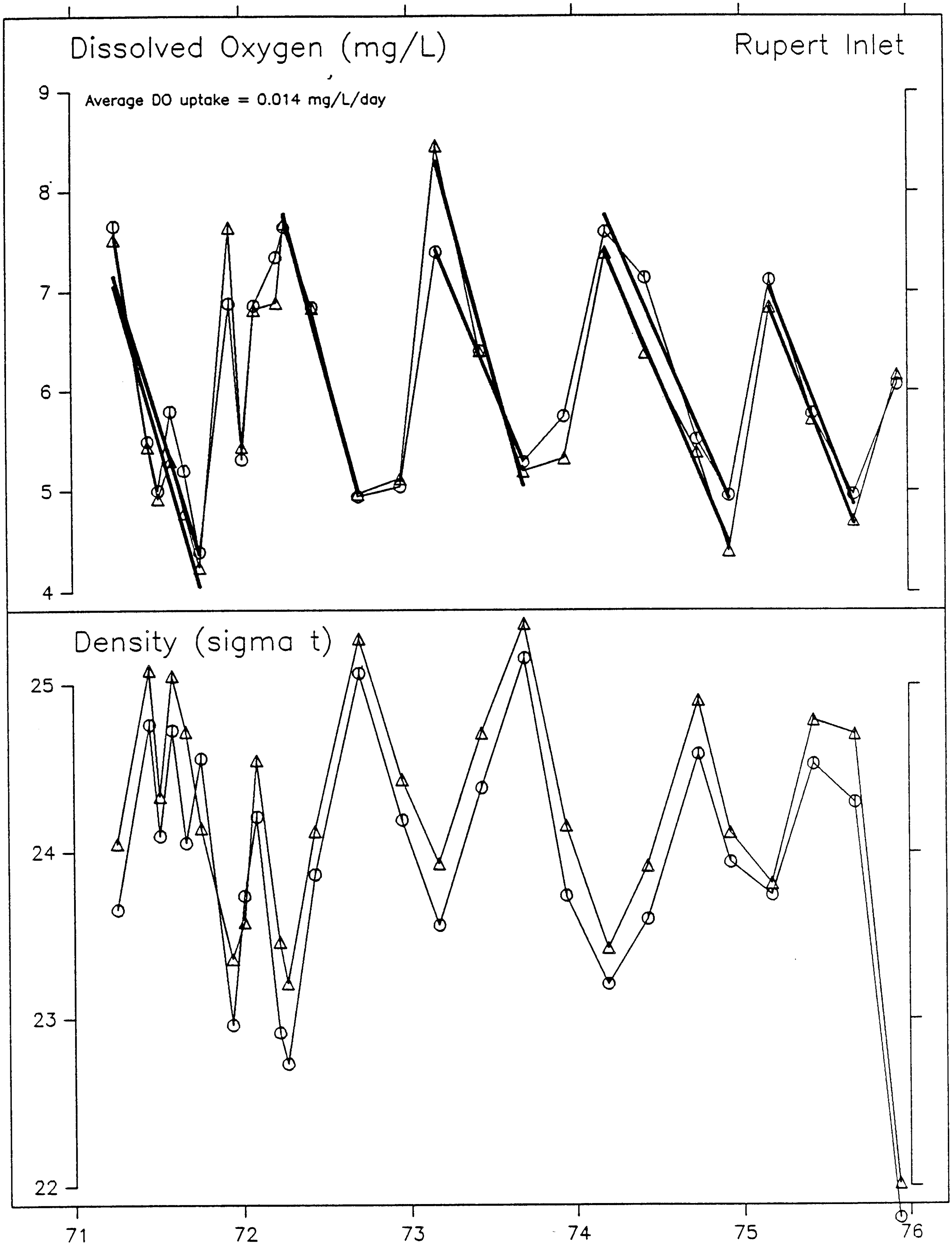


Figure 2.7 Dissolved oxygen concentration and density in Rupert Inlet (circles - 60 m; triangles - 105 m).

decrease approximately linearly during the next six months or so. Following a minimum in the oxygen level in mid to late fall, the concentration increases through the winter, and a new cycle begins.

An upper limit on the rate of oxygen consumption in the water column can be estimated by taking the slope between the maximum and minimum oxygen levels. A total of 23 least-squares fitted lines have been drawn on the three figures during these periods (3 for Indian Arm and 10 each for Saanich and Rupert Inlets). The mean slopes are 0.026, 0.029, and 0.014 mg/L/day for Indian Arm, Saanich Inlet and Rupert Inlet. Assuming that advective and diffusive processes are negligible, this rate may be ascribed to oxygen demand in the water column. Some support for this assumption is provided by the density plots for Saanich Inlet and Indian Arm which show small variability at depths and times for which lines were fitted. However, large fluctuations in the density for Rupert Inlet suggest advective processes are taking place. Still, the mean slope provides our best estimate of the upper limit for the rate of oxygen consumption in the water column.

2.4 Expected Evolution of the Flooded Pit

If the channel connecting Rupert Inlet to the pit is designed so that its bottom is below lowest low water, and the flow through the channel is not regulated, then it will take approximately 40 days for the pit to fill. Since the density of water in Rupert Inlet would not normally change significantly over this time period, we expect that the initial distribution of properties in the pit will be nearly homogeneous.

Once filled, the dynamic behaviour of the pit is expected to be similar to other inlets along the British Columbia coastline. Tides and surface winds will provide energy for mixing, while exchange with Rupert Inlet through the channel will alter the salinity, temperature (and hence the density) and concentrations of dissolved gases in the water. Initially, there will be no life in the flooded pit; hence detritus in the water column will be limited, and there will be little deposition of sediments on the bottom. Consequently, there will be negligible depletion of dissolved oxygen immediately after flooding. As pelagic and benthic organisms establish communities, addition of oxygen by phytoplankton, and depletion by bacteria will become significant. Depletion will be compensated to an unknown degree by reaeration through the surface and by influxes of oxygenated water from outside the pit. A description of the expected chemical evolution and oxygen balance in the pit is presented in Appendix A.

3.0 MINE PIT MODEL FORMULATION AND SOLUTION METHODS

In light of the physical oceanographic processes discussed in Chapter 3, and with the need to simulate the evolution of the pit over a decade or more, a numerical model has been developed to forecast the vertical distribution of three state variables: salinity, temperature and dissolved oxygen. The basic structure of the model consists of a set of 96 stacked, horizontal layers of identical thickness, Δz, equal to 4.064 m (i.e., 3 layers per 40 ft bench). Each state variable is defined at the centre of a layer, while the vertical diffusion coefficient and the horizontal area of the pit are defined at the bottom edge of a layer (Fig. 3.1).

3.1 Basic Assumptions

In order to develop a model that would execute relatively quickly, and have a small number of adjustable parameters, a number of simplifying assumptions have been made:

- All properties of the flooded pit are horizontally homogeneous at all times, that is, they are functions of depth (z) and time (t) only.
- The effect of all currents, apart from density flows, on the temporal and spatial distribution of water properties may be parameterized in a single, vertical turbulent diffusion equation. Thus, the velocity field in the flooded pit may be excluded.
- The value of the vertical turbulent diffusion coefficient varies with depth and time, is solely a function of the local stratification, and may be calculated directly from the static stability.
- Intrusions of dense water into the flooded pit from Rupert Inlet flow down the pit sides and mix with the in situ water over a time period that is less than the model time step.
- The surface temperature of water in the pit is identical to the surface temperature in Rupert Inlet.
- The effect of wind on modifying the surface oxygen flux or upper layer mixing rate is ignored.
- Fresh water runoff into the pit mixes completely with the surface layer, modifying only the salinity as it does so.
- If water in the channel is less dense than water in the pit at the surface, then the two volumes mix completely in the surface layer of the pit over one model time step.
- The rate of benthic oxygen demand is constant at all times, and on all horizontal surfaces in the pit.
- Benthic oxygen consumption affects only the water in the layer adjacent to each horizontal surface, and within each layer, only that fraction of water directly above the local bottom. The remaining, unaltered water at that level is then mixed completely with the depleted water over one model time step.

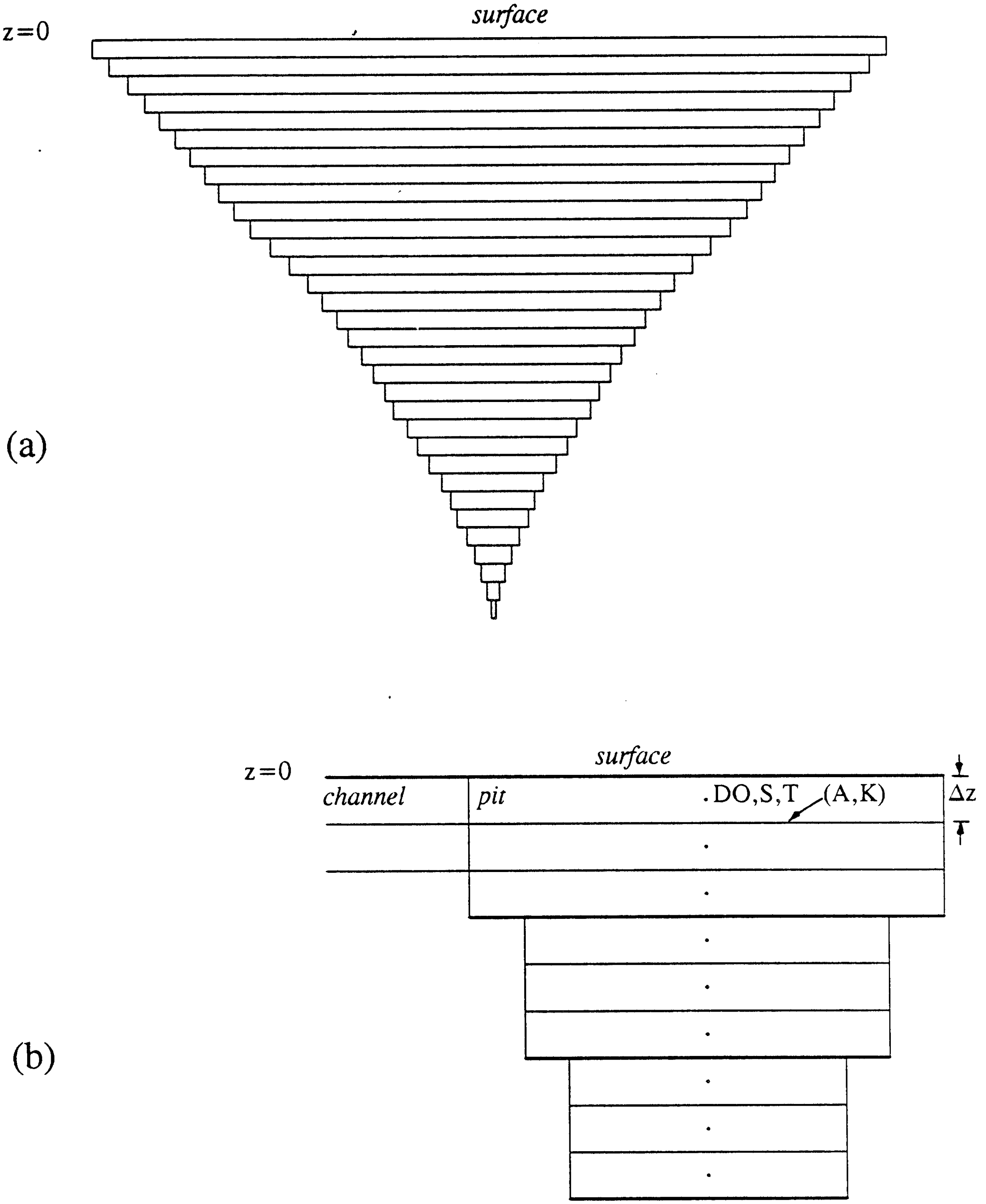


Figure 3.1 (a) Model representation of open pit mine as a set of 32 stacked layers. (b) Distribution of model parameters for first three layers (9 sublayers).

- The oxygen demand in the water column is zero from the surface to 30 m depth, and falls within two temporal regimes below this depth. From April through September the rate is set to a constant, relatively large value. During the remainder of the year it is set to one half of this value. This reflects the seasonal cycle in dissolved oxygen discussed in Section 2.3.

3.2 Governing Equations

3.2.1 Density

Density is calculated using the International Equation of State as a nonlinear function of salinity, temperature, and pressure (depth). Due to the large variations in salinity near the coast, the density tends to be dominated by the salinity terms in the equation.

3.2.2 Vertical Diffusion

The vertical diffusion equation, which includes varying horizontal area and vertically varying diffusion coefficient, is given by

$$\frac{\partial X}{\partial t} = \frac{1}{A} * \frac{\partial}{\partial z}\left[A * K * \frac{\partial X}{\partial z}\right] \tag{3.1}$$

where

X = one of temperature, salinity, or dissolved oxygen
z = depth measured downward from 0 at the surface (m)
t = time (days)
$A(z)$ = total horizontal area of the pit at depth z (m^2)
$K(z,t)$ = diffusion coefficient (m^2/day)

The form of the diffusion coefficient, K, is taken from Svensson (1979) who derived an empirical power law relating K to the static stability given by the Brunt-Vaisala frequency

$$N^2 = \frac{g}{\rho} * \frac{\partial \rho}{\partial z} \tag{3.2}$$

where

g = gravitational acceleration (m/s^2)
ρ = density of in situ water (kg/m^3)

The relationship that Svensson found for the deep waters of Byfjorden fjord in Sweden appears to be valid for a range of K values between about 0.01 and 1 m^2/day, and is given by

$$K = 1.037 * 10^{-3} * (N^2)^{(-0.6)} \tag{3.3}$$

While it is likely that K has some dependence on vertical current shear in the near surface waters, the absence of a velocity field in the model precludes our incorporating shear into the formulation. We have therefore adopted (3.3), using (3.2) to calculate N^2, for the entire range of depths.

3.2.3 Surface Reaeration

The equation governing the flux of oxygen through the surface is given by (Klein, 1962)

$$DO' = Os + (DO - Os) * \exp(-Kr * \Delta t) \tag{3.4}$$

where

Δt = time interval (days)
DO = initial concentration of oxygen in the surface layer (g/m^3)
DO' = oxygen concentration after time interval Δt (g/m^3)
Os = saturation concentration of oxygen (g/m^3)
Kr = rate constant set to 0.5 (day^{-1})

The saturation concentration of oxygen, Os, is given by the UNESCO standard oceanographic formula as a function of temperature and salinity.

3.2.4 Oxygen Consumption

Benthic oxygen demand is present at each horizontal bench and at the bottom of the pit. The expression for dissolved oxygen concentration is given by

$$DO' = \begin{cases} DO - \dfrac{F_1 * Ah * \Delta t}{V} & DO > \dfrac{F_1 * Ah * \Delta t}{f * V} \\ (1-f) * DO & DO \leq \dfrac{F_1 * Ah * \Delta t}{f * V} \end{cases} \tag{3.5}$$

where

Ah = horizontal, BOD containing area of the bench or bottom (m^2)
f = fraction of horizontal area covered by BOD (= Ah/A)
V = volume of the layer (= $A * \Delta z$) (m^3)
F_1 = benthic oxygen demand ($g/m^2/day$)

In situ oxygen demand is prescribed by

$$DO' = DO - F_2 * \Delta t \tag{3.6}$$

where

F_2 = in situ oxygen demand ($g/m^3/day$)

3.2.5 Fresh Water Runoff

Fresh water runoff into the pit is included as a modification to the surface layer salinity, that is

$$S' = \frac{S * Vs}{Qf * \Delta t + Vs} \tag{3.7}$$

where

S = initial salinity in the upper layer (ppt)
S' = salinity in the upper layer after time Δt (ppt)
Vs = volume of the surface layer (m^3)
Qf = fresh water influx (m^3/day)

3.2.6 Density Currents

The equations for the flow of dense water down the slope of the pit are based on the idea that two forces--reduced gravity and frictional drag--act to accelerate the flow. This is expressed as

$$a = g' - Cd * U^2 \tag{3.8}$$

where

a = along-slope acceleration (m/s^2)
$g' = (g * \Delta\rho/\rho) * \sin(\theta)$ (3.9)
U = along-slope speed (m/s)
θ = mean angle of the slope above horizontal
$\Delta\rho$ = density difference between flow and in situ water (kg/m^3)
Cd = drag coefficient combining effects of bottom and interfacial friction

The time required for the flow to travel a vertical distance Δz equal to the thickness of one layer in the model is given by

$$t = \frac{[U^2 + 2a * \Delta z/\sin(\theta)]^{(0.5)} - U}{a} \tag{3.10}$$

Because (3.8) leads to an unstable solution if used in the model, one of the U values in the quadratic term is replaced by the velocity at the time t later, that is by

$$U' = U + at \tag{3.11}$$

Combining (3.8), (3.10) and (3.11) yields

$$a = g' - Cd * U * [U^2 + 2a * \Delta z/\sin(\theta)]^{0.5} \tag{3.12}$$

Using (3.8) to provide an initial guess, (3.12) is iteratively solved for a, which is then used in (3.10) and (3.11) to find t and U'.

The result of this sequence of steps is a value for the flow velocity at a depth Δz below the previously known value. By this means the flow velocity is calculated at each layer in the model, and the time required to reach that layer from the start of the inflow is determined. The values for the flow velocity, U, are required to calculate the entrainment of ambient water into the flow. The volume of water entrained during the interval, t, required for the flow to travel vertically through one layer is given by (Bo Pedersen, 1980)

$$Ve = Ke * Af * U * t \tag{3.13}$$

where

Ve = volume of water entrained (m^3)
Ke = entrainment coefficient
Af = surface area of the flow over which entrainment occurs (m^2).

The value of Ke depends on the bottom slope, and is given by (Bo Pedersen, 1980)

$$Ke = 0.070 * \sin(\theta) \tag{3.14}$$

The surface area, Af, will depend on the shape of the flow, but has been approximated using

$$Af = Vf/Hc \tag{3.15}$$

where

Vf = flow volume (m^3)
Hc = channel depth (m)

The flow volume, Vf, increases from its initial value at channel depth until the point where U is no longer positive, that is, at a level where the flow ceases. As the volume, Ve, of water is entrained, the three state variables, and the flow volume are modified according to

$$X' = \frac{Vf * X + Ve * Xa}{Vf + Ve} \tag{3.15}$$

$$Vf' = Vf + Ve \tag{3.16}$$

where

X = one of temperature, salinity, or dissolved oxygen in the flow prior to entrainment
X' = value of X in the flow after entrainment
Xa = value of X in the pit at the relevant depth
Vf = volume of flow prior to entrainment (m^3)
Vf' = volume of flow after entrainment (m^3)

After stopping, the waters of the flow are mixed completely with the ambient water at that level using a relationship similar to (3.15), that is

$$X' = \begin{cases} X & Vf > V \\ \dfrac{Vf * X + (V-Vf) * Xa}{V} & Vf < V \end{cases} \tag{3.16}$$

If Vf > V, then after (3.16) is applied at the intrusion depth Vf is reduced by V. Equation (3.16) is then applied to the layer immediately above, and this process continues for shallower layers, until the surface is reached. In this way the effect of the intrusion is to lift the waters of the pit upward, and to drain from the surface layer an amount of water equal in volume to the volume of the inflow. The vertical movement is manifested in the mixing of adjacent layers.

3.3 Boundary Conditions

The periodic cycles of salinity, temperature, and dissolved oxygen discussed in Section 2.2.3 were used to provide daily values to the model at the entrance to the channel. Vertical profiles were then integrated to yield a single average value representative of complete mixing within the channel. The initial runs using these simple boundary data were used to investigate the sensitivity of solutions to various parameters. More realistic results on the evolution of the pit waters were produced by prescribing the non-periodic boundary data discussed in Appendix B.

The surface temperature within the pit was set to the observed surface temperature in Rupert Inlet, while the oxygen flux at the surface was implemented using (3.4).

3.4 Initial Conditions

The initial values of salinity, temperature and dissolved oxygen are set equal to their values in the channel at the start time. This is a valid assumption provided that complete vertical and horizontal mixing occurs during the filling stage. Density is then calculated at each depth in the model using the equation of state for sea water.

3.5 Solution Method

The model calculates a solution to the governing equations each simulated day beginning at a specified month and day. Vertical profiles of salinity, temperature, and dissolved oxygen are stored periodically at a frequency that depends on the length of the simulation. These may then be analyzed or plotted to examine the evolution of the water properties of the pit.

An explicit finite difference scheme is used to solve the diffusion equations for salinity, temperature and dissolved oxygen. Conservation of each variable is ensured by setting the gradients at the surface and bottom to zero. Tests of the model confirm that in the absence of sources or sinks the system preserves the total amount of each state variable over arbitrarily long time periods.

Initial model runs revealed that a fixed 1-day time step, while providing adequate temporal resolution during the bulk of each simulation, proved too large to resolve the deep intrusion events. For this reason, an adaptive scheme was implemented to detect rapid and deep intrusion of water into the pit, and then automatically reduce the model time step during these episodes.

4.0 HYDRODYNAMIC MODEL OF THE PIT AND CHANNEL

4.1 Assumptions

The hydrodynamic behaviour of the pit and its connecting channel to the inlet was investigated with a two-dimensional, depth-averaged numerical model (C2D). The pit geometry was determined from the "Ultimate Pit" drawing dated April 23, 1990, assuming that the 1000 foot contour is approximately mean sea level. The connecting channel was aligned roughly perpendicular to the southeast end of the 860 ft. bench. The opening was located at (25250E,4400N) in terms of the "Ultimate Pit" coordinates. The channel geometry was specified as

width: 100 ft.
depth: 40 ft. (or 960 relative to the 1000 ft. datum)
length: 800 ft.

Between 600 and 800 ft., the channel gradually opened to the west to a 400 ft. wide, 40 ft. deep channel mouth. The model domain in plan view is shown in Fig. 4.1.

Only tides and Coriolis were considered as potential hydrodynamic forces, thereby neglecting wind and density (baroclinic) effects. Both bottom friction and horizontal eddy diffusion are included in the formulation.

4.2 Model Formulation

C2D is a numerical model of water levels and depth-averaged circulation in two horizontal dimensions. The equations that embody the model's physics are expressions of conservation of mass and momentum. The former equation defines the time-dependent rate of change of sea surface elevation at any location as a function of the flux of water in both horizontal directions past that point:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial ud}{\partial x} + \frac{\partial vd}{\partial y} = 0$$

The momentum equations, one for each spatial dimension, define the temporal rate of change of horizontal velocity in terms of non-linear horizontal velocity gradients, hydrostatic pressure gradient, Coriolis force, and bottom stress. In the x-direction (visualized as positive to the east):

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial \zeta}{\partial x} - fv + K_f\frac{u(u^2+v^2)^{1/2}}{d} = 0$$

with an equivalent equation for the y-direction.

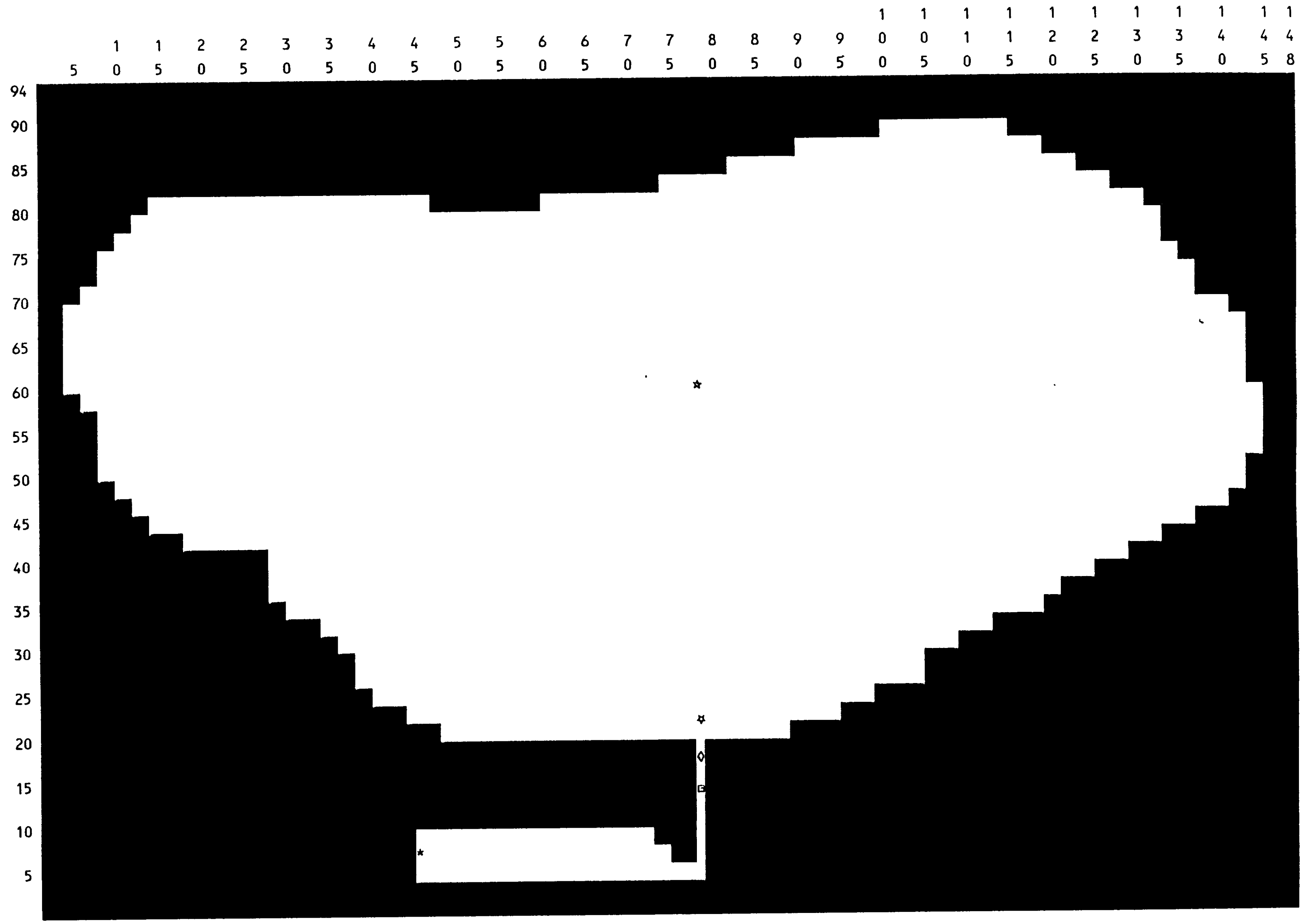


Figure 4.1 C2D grid layout of the Island Copper Mine Ultimate Pit.

The variables are defined as:

ζ	surface elevation about mean sea level (m)
u	x-component of current (m/s)
v	y-component of current (m/s)
d	total water depth (m)
t	time (s)
x	horizontal distance (positive to the east) (m)
y	horizontal distance (positive to the north) (m)
g	gravitational acceleration (9.81 m/s^2)
f	Coriolis parameter ($1.46 \times 10^{-4} \sin \phi$) (Hz)
ϕ	central latitude of the model grid (rad)
K_f	bottom friction coefficient (dimensionless)

The friction coefficient is typically of the order of 0.003 but may be several times greater in very shallow areas.

The solution of the differential equations is formulated in terms of differences in a manner suggested by Leendertse (1967) and later tested by Hodgins (1977). The numerical difference scheme is time- and space-centred, and being fully implicit, the only restriction on the time step and grid dimension is that the modelled waveform (i.e., the tide) must be well resolved in time and space. The model was shown (Hodgins, 1977) to be unconditionally consistent with the differential equations and to be second-order accurate (i.e., to have truncation errors of $O(\Delta t^2, \Delta x^2, \Delta y^2)$). The one-dimensional non-linear equations without frictional dissipation are analytically unconditionally stable.

For applications with strong non-linear flow fields, horizontal eddy viscosity terms are added to model horizontal momentum diffusion caused by turbulence:

$$\frac{\partial u}{\partial t} = K_H \cdot \left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right]$$

where K_H is the horizontal eddy diffusion coefficient (m^2/s).

The numerical computation is applied to the independent solution field of the mass and momentum equations.

4.3 Application of C2D

4.3.1 C2D Set-up Summary

In all reported runs of C2D, the following parameters were used:

grid dimensions: 148 by 94

grid size: 15.24 m (50 ft.) between calculation points (e.g., u and ζ or v and ζ)
30.5 m (100 ft.) between like calculations points (e.g., from one ζ to the next closest ζ)

time step: 5 s

central latitude: 50°N

friction coefficient: $K_f = 0.003$

horizontal eddy diffusion coefficient: $K_H = 2.5\ m^2/s$

boundary conditions: elevation (ζ) along the open sea entrance applied uniformly along the boundary, but varying at the time step of the model

initial conditions: the model initially starts from rest ($u = v = \zeta = 0$); spinup to reach equilibrium required about 12 hours of model time

4.3.2 Boundary Conditions

The boundary condition was constructed from a straightforward superposition of the seven principal tidal harmonic constituents provided by the Canadian Hydrographic Service for the Makwazniht Island tide gauge station. The result is a mixed tide with an approximate maximum range of ±2.2 m. A 30-day portion of this tidal signal is shown in Fig. 4.2; the mean elevation of this time-series is zero.

For modelling purposes, three portions of this 30-day tide were extracted: one for spinup of the model, one for a typical neap tide simulation, and one for a large spring tide run. The spinup period was chosen to end at exactly mean water level on a falling tide. Both the neap and the spring periods commenced from a mean water level, falling tide. The neap tide run began on day 6, hour 10:00 (with reference to Fig. 4.2), and the spring tide run started on day 25, hour 14:18. Plots of the imposed boundary elevation are included with the model results in the next section.

4.4 Discussion of Results

To assess the tidal behaviour of the channel and pit, time-series model results were analyzed at five particular points (which are identified in Fig. 4.1). Water level response has been plotted for the boundary, the mid-channel point (model grid [78,14]), the channel exit (model grid [78,18]), and the mid-pit location [78,60]. Figure 4.3 illustrates the relative tidal responses for both neap and spring tides. Water elevations in the channel and in the pit are essentially identical in magnitude and only slight phase variations are predicted. Relative to the boundary (Rupert Inlet), the tide in the pit lags by approximately one hour and maxima are attenuated by 4 to 10%. The largest modelled attenuation was about 16 cm, in the spring tide.

Depth-averaged velocity in the pit diminishes rapidly with distance from the channel exit. Figure 4.4 shows the velocity component that is aligned with the channel (i.e., model north-south) for the two channel output points (Fig. 4.1: model grids [78,14] and [78,18]) and for a third point just inside the pit at [78,22]. Maximum velocities in the channel are at the exit and approach 1.5 m/s during spring tides. At mid-channel, the speed is about 15% lower at the peaks. Just inside the pit, velocity maxima are less than a third of the channel exit velocities.

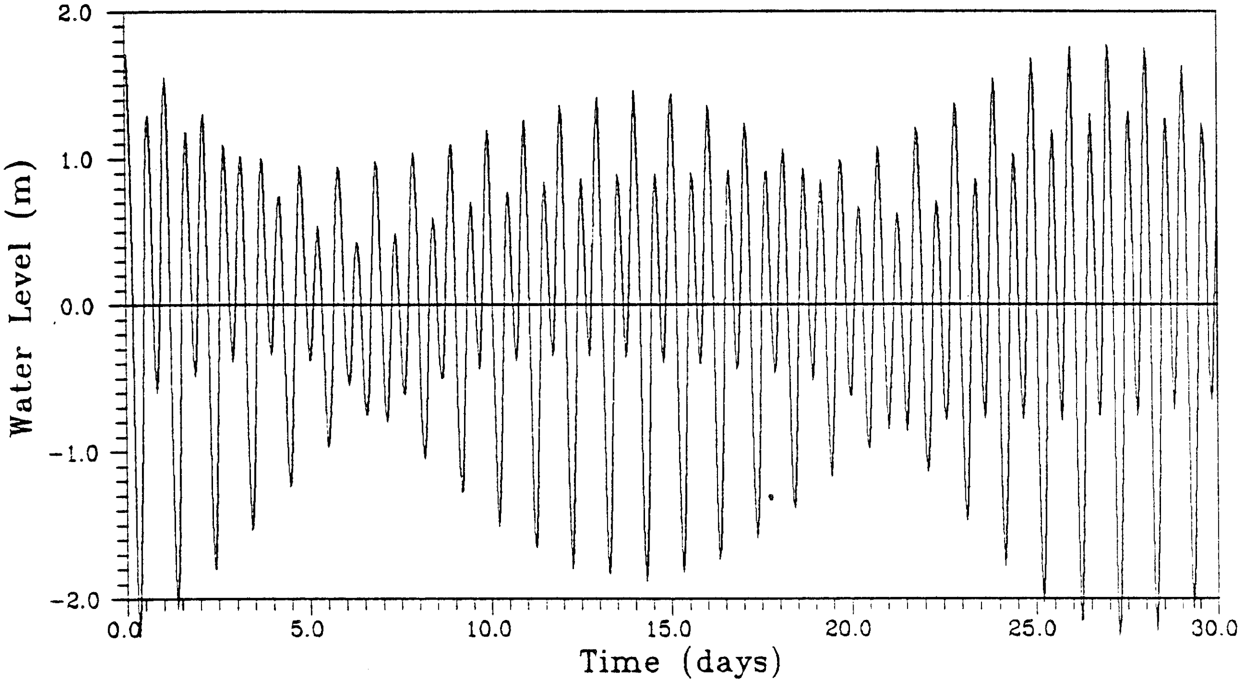
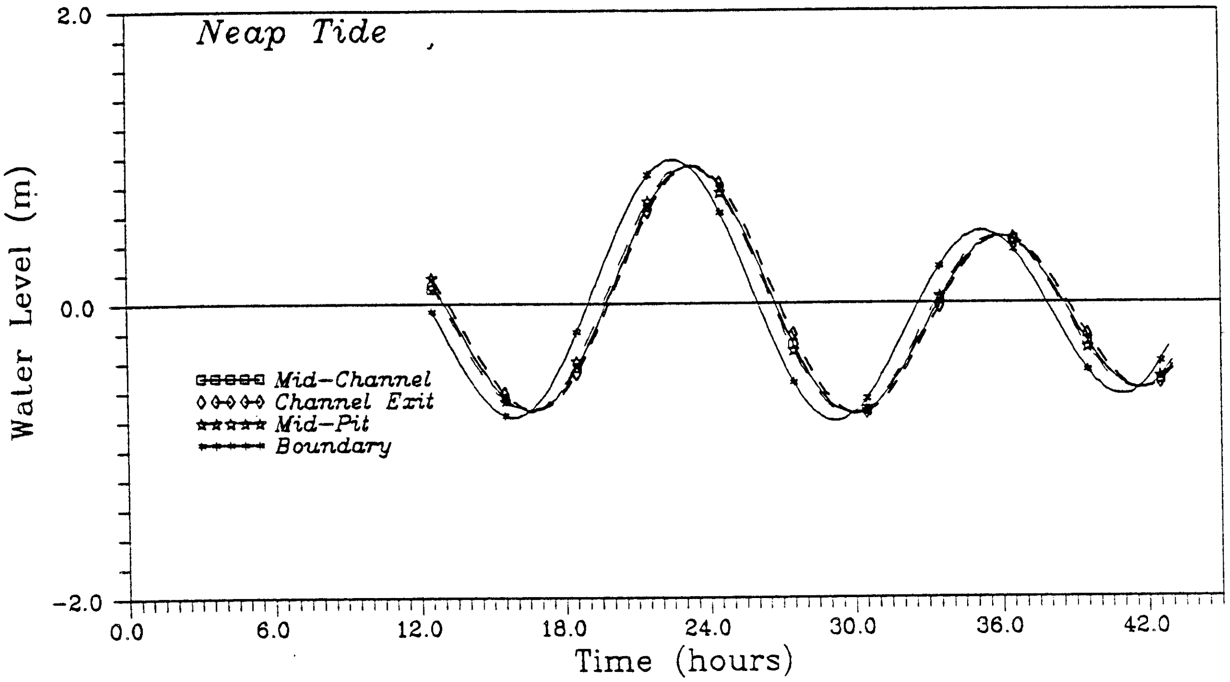


Figure 4.2 The tidal boundary condition.



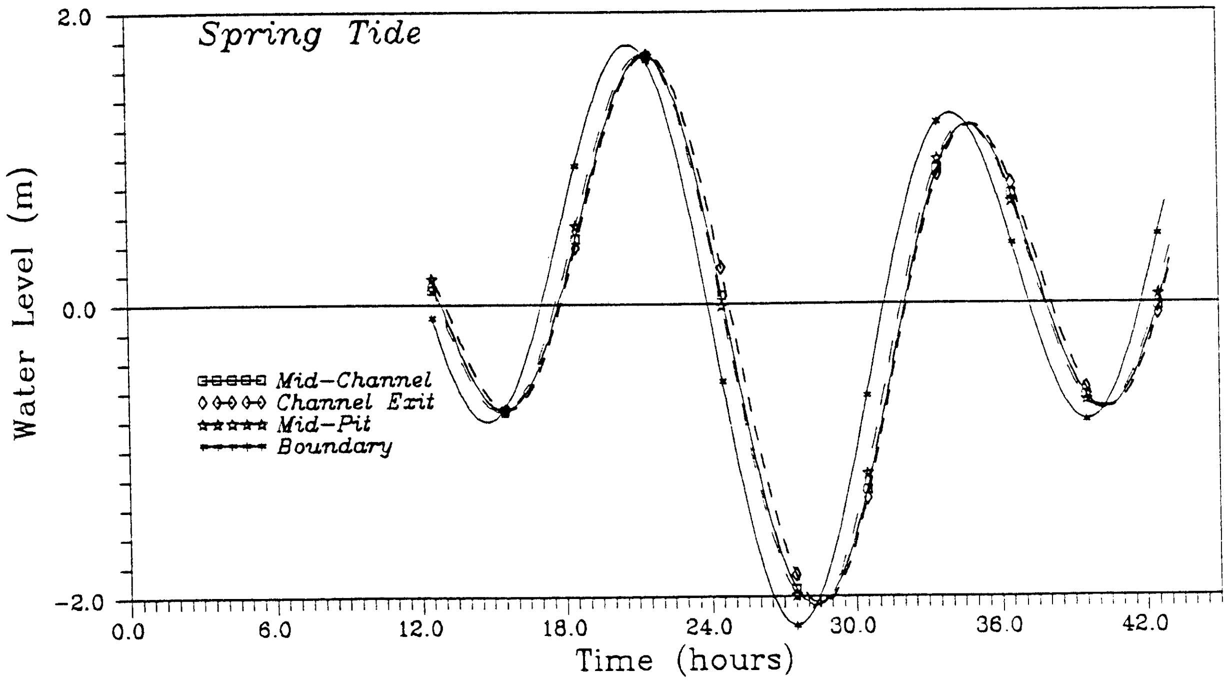


Figure 4.3 Modelled water levels at various points in the channel and pit for representative neap and spring tides.

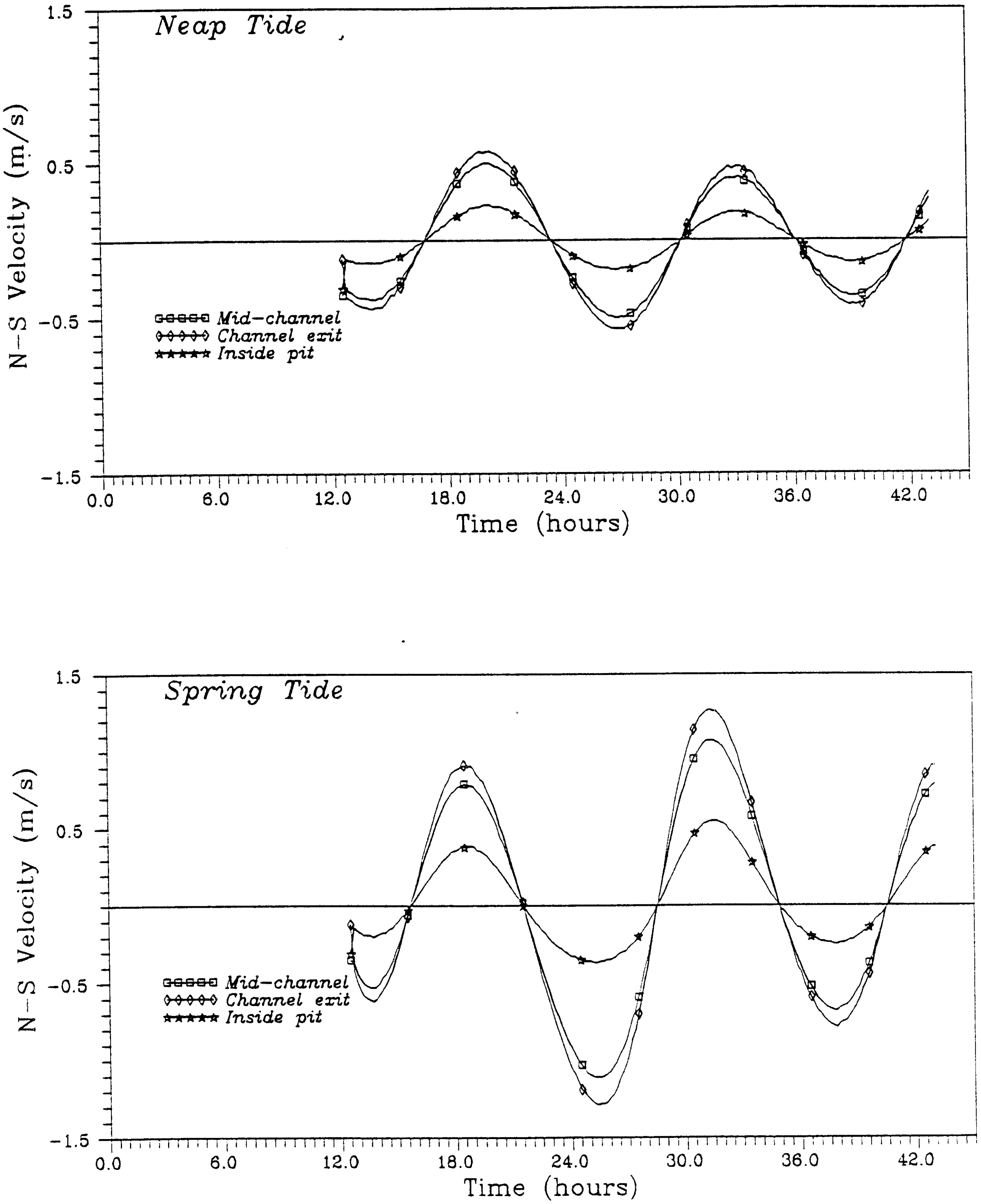


Figure 4.4 Modelled current speeds, aligned with the channel, at selected points in the channel and pit for representative neap and spring tides.

5.0 MINE PIT SIMULATIONS

5.1 Initial Runs: Periodic Boundary Conditions

A total of 7 simulations were carried out using the pit model with various combinations of channel depth, oxygen demand rates, and start times. Channel depths of 4.06, 8.12, 12.18, and 16.24 m were used (1 to 4 model layers), together with three different sets of oxygen uptake rates. In addition, two start times were used; the first, on January 16, corresponds to the time of minimum density in the channel, while the second, on September 16, corresponds to the time of maximum density. Table 5.1 summarizes the parameter settings for each simulation. The duration of all runs was 50 years.

Figures 5.1 to 5.7 show the dissolved oxygen concentrations from each simulation. Figures 5.1 to 5.6 correspond to runs which began at the time of minimum density in the channel, while Fig. 5.7 corresponds to initial conditions at the time of maximum density. Each figure consists of an upper plot with vertical profiles of dissolved oxygen and a lower plot of the spatial and temporal distribution of dissolved oxygen. Bold lines are spaced ten years apart. Model results were saved at a rate of two sets of dissolved oxygen, temperature and salinity per month. A digital, weighted moving-average filter was applied in the time domain (Graham, 1963) prior to plotting in order to filter out fluctuations at periods less than subsampling rate of two profiles per year.

Comparing Fig. 5.5, and 5.6 we see that varying the oxygen uptake rates by a factor of three has little impact on the final distribution of oxygen in the pit. For this reason all other runs were made using the average of these two sets of values.

Some general features are common to the results from most of the simulations. After 50 years, the vertical oxygen distribution consists of an oxygenated surface layer that extends down to between 150 and 200 m. Maximum dissolved oxygen levels occur at the surface, with values decreasing downward to anoxic conditions in the deeper layers. It is also apparent that, ultimately, there is little difference in dissolved oxygen between infilling with maximum or minimum density sea water.

5.2 Final Runs: Realistic Boundary Conditions

Ten simulations (runs 8 to 17) were completed using the more realistic boundary conditions generated by the stochastic model discussed in Appendix B. Model input parameter settings are listed in Table 5.1. The duration of each run was 200 years with the start time set to January 1, 1972, for runs 8 to 11 and October 28 for runs 12 to 17. We recall that these boundary data consist of a random component superimposed upon an underlying mean having a period of 17 years.

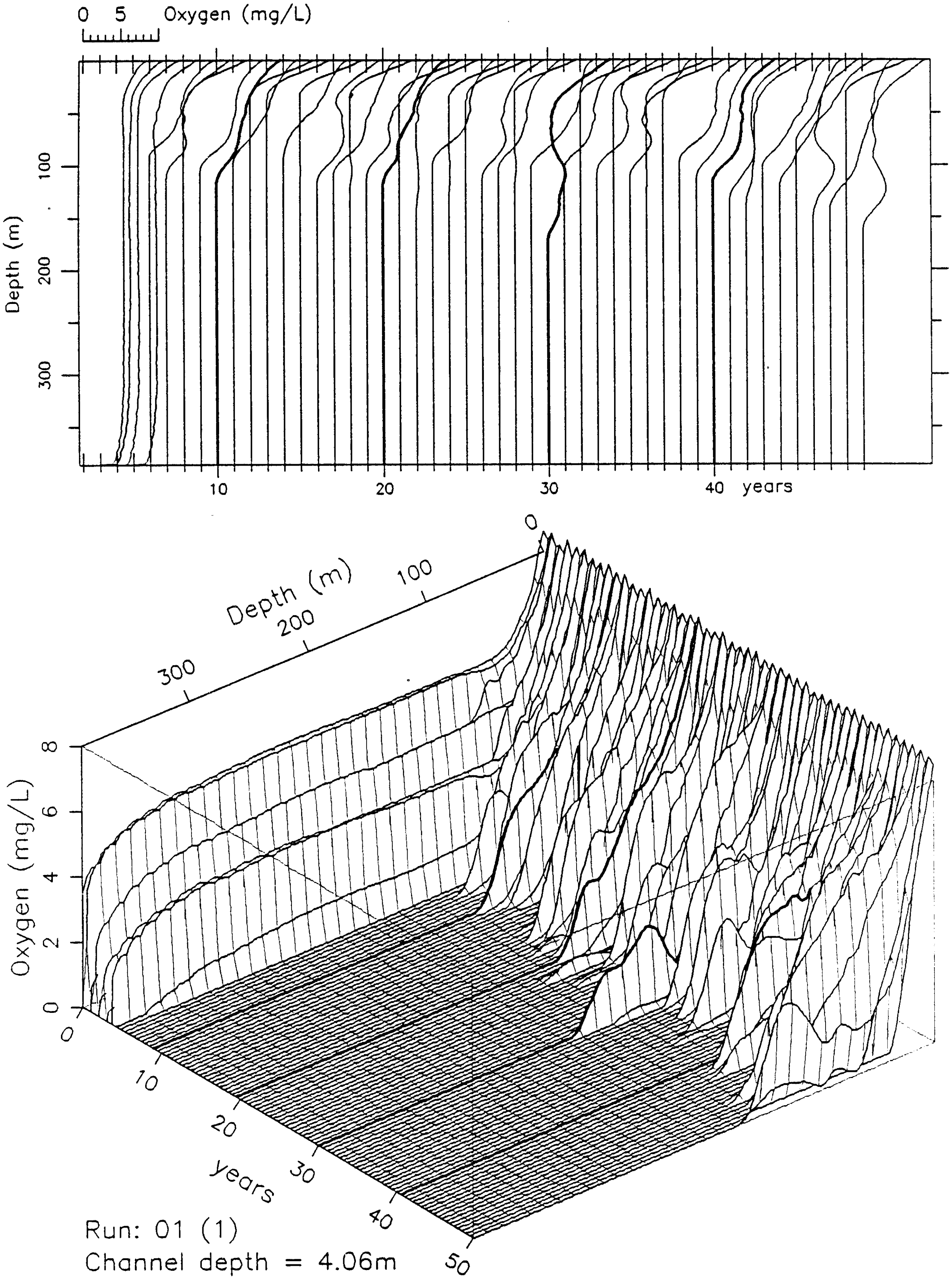
The results of these runs are presented in Figs. 5.8 to 5.17 which consist of time-series plots of dissolved oxygen at various depths in the pit. Points are plotted semi-monthly, and the two ticks on each vertical axes correspond to 5 and 10 mg/L.

The figures reveal that oxygen levels down to about 25 m are generally greater than 5 mg/L throughout the duration of the simulations. For runs 9 to 11 (channel depths greater than 8 m) there are rare instances when anoxic conditions result at this depth. At a depth of 50 m, the

Table 5.1

Parameter Settings for Pit Model Simulations

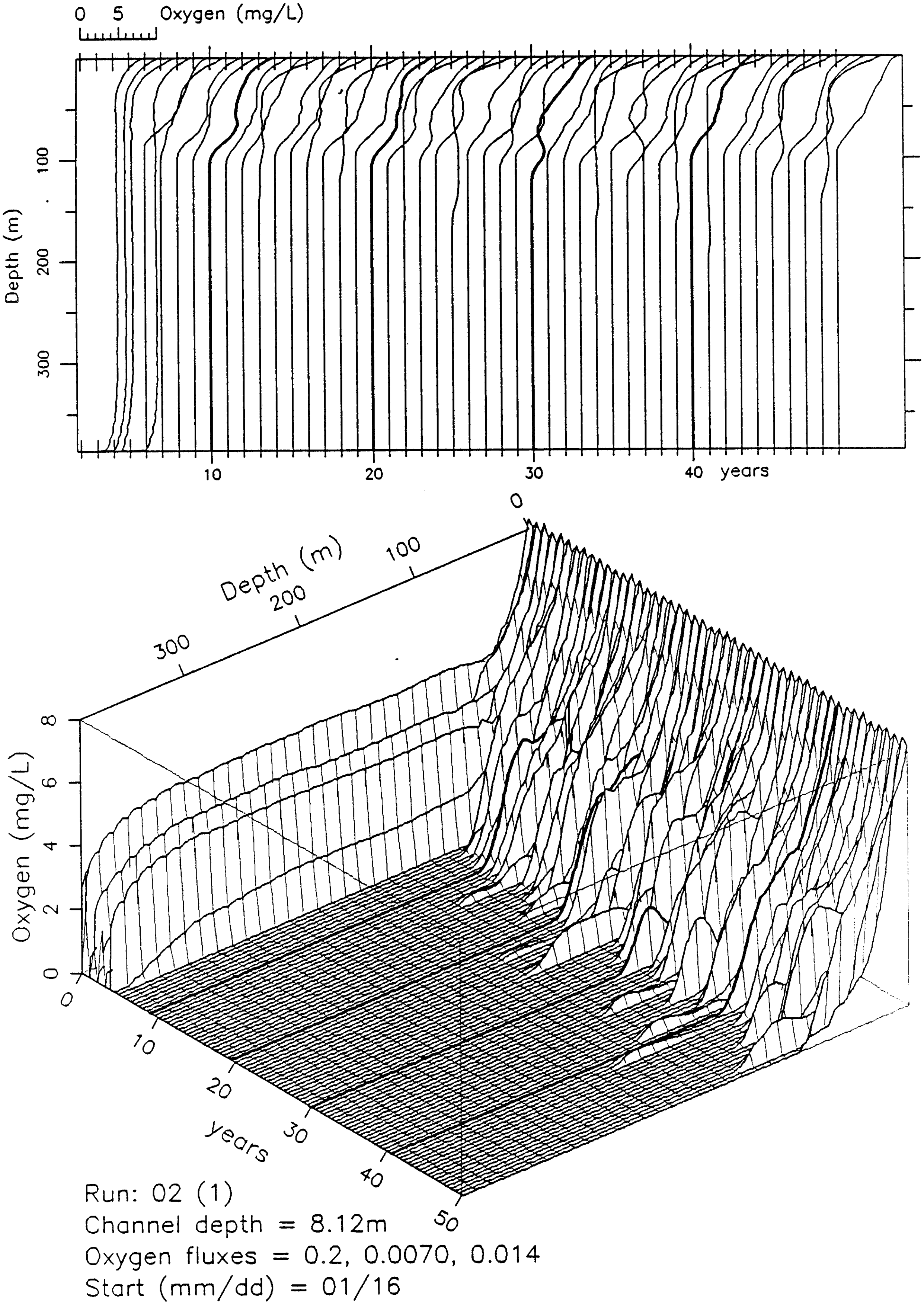
No.	Start mm/dd	Dissolved Oxygen Demand Benthic (g/m²/d)	In Situ (g/m³/d) Winter	Summer	Channel Depth (m)	Turb. Mixing Coeff (K) Scaled by
(periodic boundary conditions)						
1	01/16	0.2	0.0010	0.014	4.06	1
2	01/16	0.2	0.0010	0.014	8.12	1
3	01/16	0.2	0.0010	0.014	12.18	1
4	01/16	0.2	0.0010	0.014	16.24	1
5	01/16	0.1	0.0005	0.007	12.18	1
6	01/16	0.3	0.0015	0.021	12.18	1
7	09/16	0.2	0.0010	0.014	12.18	1
(non-periodic boundary conditions)						
8	01/01	0.2	0.0070	0.014	4.06	1
9	01/01	0.2	0.0070	0.014	8.12	1
10	01/01	0.2	0.0070	0.014	12.18	1
11	01/01	0.2	0.0070	0.014	16.24	1
12	10/28	0.2	0.0250	0.050	8.12	10
13	10/28	0.2	0.0250	0.050	8.12	1
14	10/28	0.2	0.0105	0.021	8.12	10
15	10/28	0.2	0.0105	0.021	8.12	1
16	10/28	0.2	0.0070	0.014	8.12	10
17	10/28	0.2	0.0070	0.014	8.12	1



Run: 01 (1)
Channel depth = 4.06m
Oxygen fluxes = 0.2, 0.0070, 0.014
Start (mm/dd) = 01/16

09:24 Sep 13, 1990

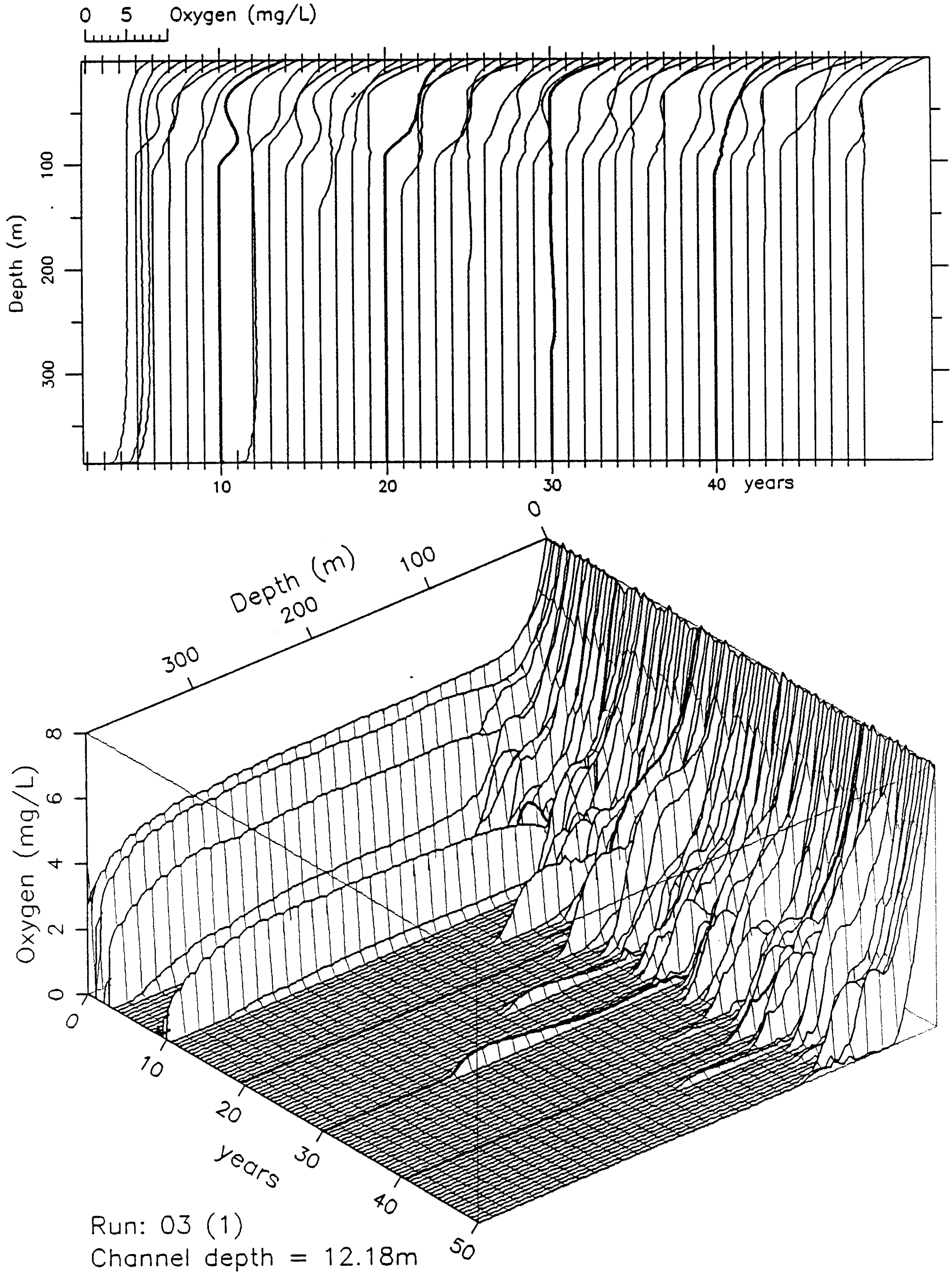
Figure 5.1 Annual vertical profiles (top) and depth-time surface (bottom) of dissolved oxygen from simulation 1.



Run: 02 (1)
Channel depth = 8.12m
Oxygen fluxes = 0.2, 0.0070, 0.014
Start (mm/dd) = 01/16

10:31 Sep 13, 1990

Figure 5.2 Annual vertical profiles (top) and depth-time surface (bottom) of dissolved oxygen from simulation 2.



Run: 03 (1)
Channel depth = 12.18m
Oxygen fluxes = 0.2, 0.0070, 0.014
Start (mm/dd) = 01/16

11:51 Sep 13, 1990

Figure 5.3 Annual vertical profiles (top) and depth-time surface (bottom) of dissolved oxygen from simulation 3.

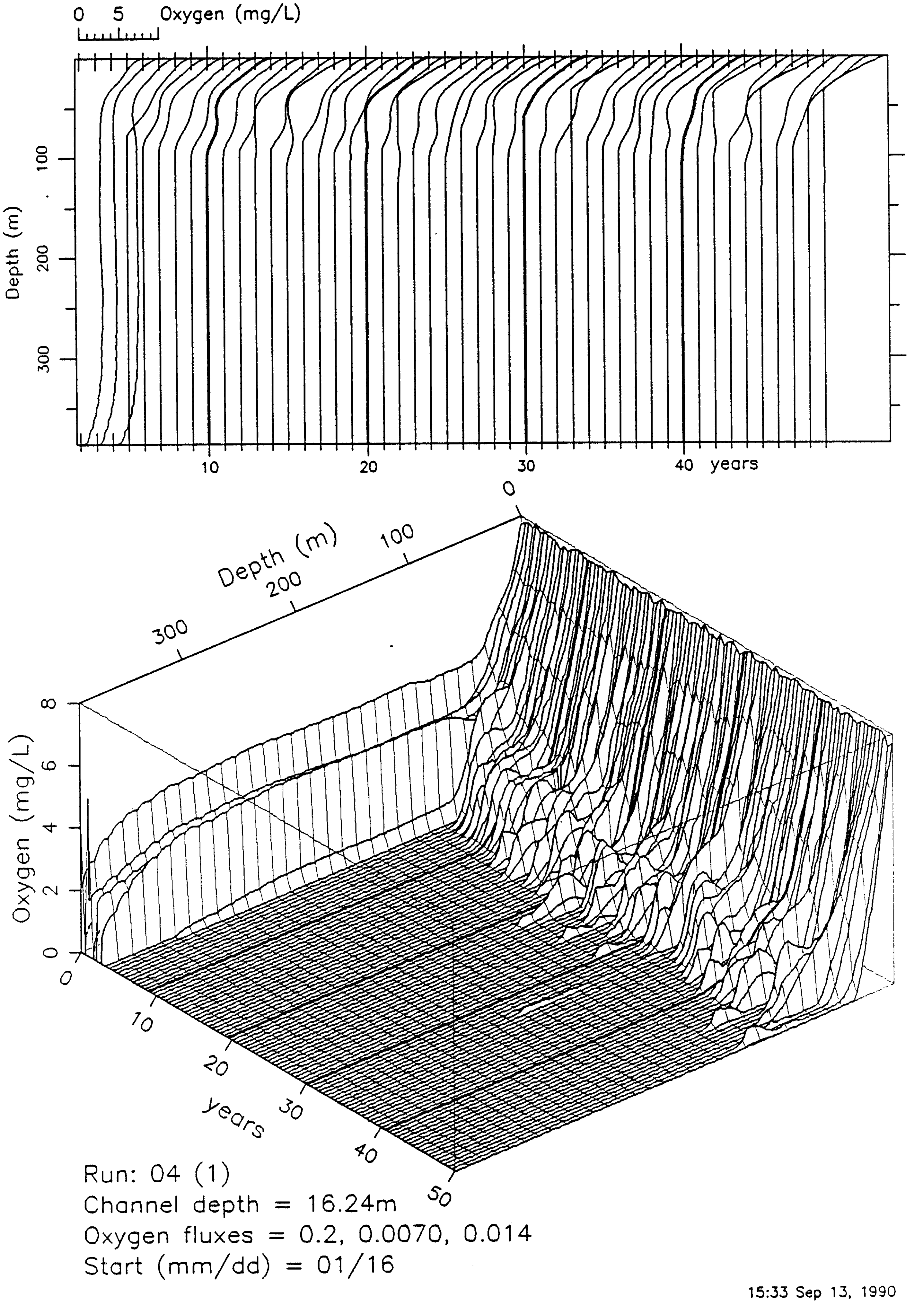
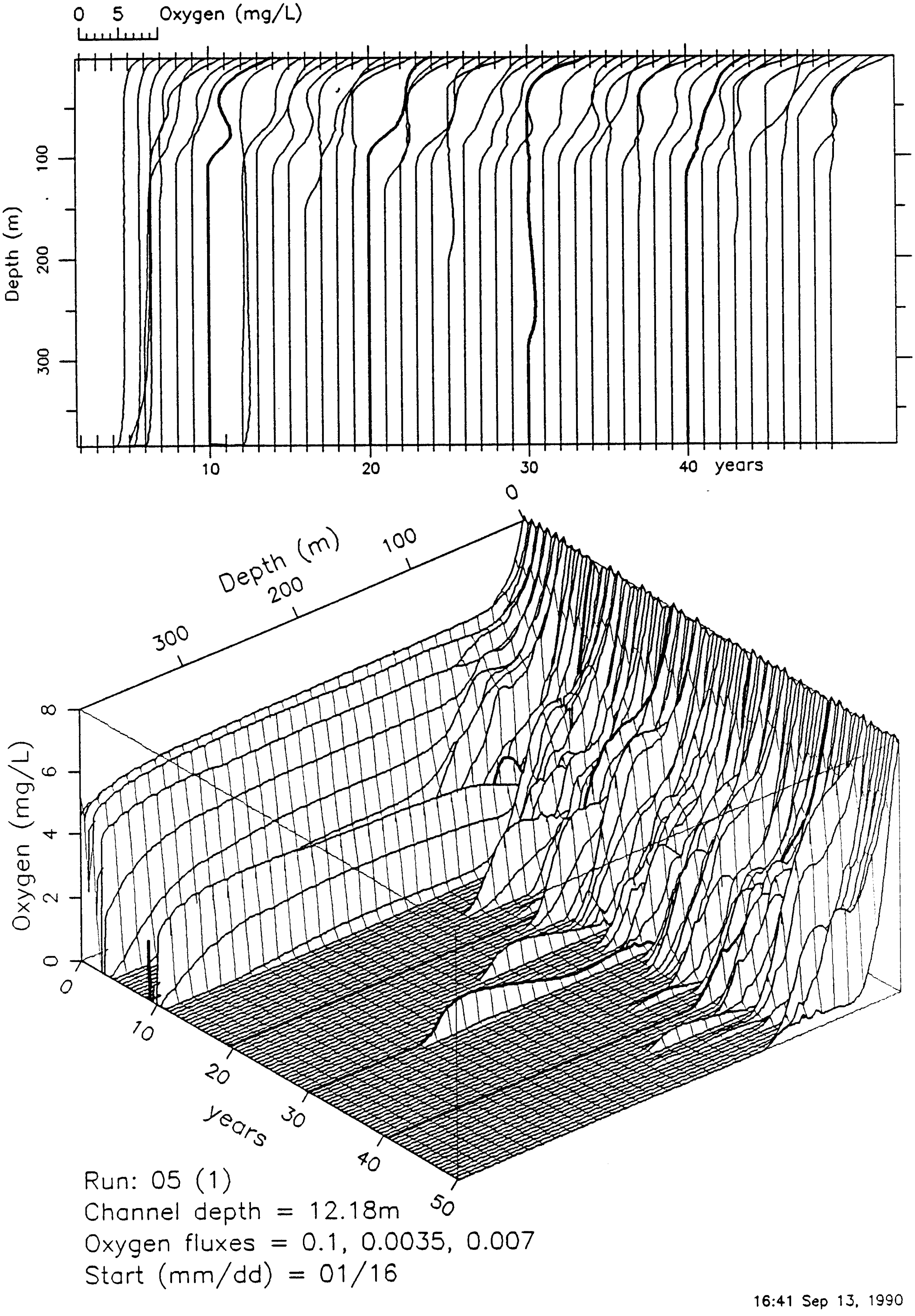


Figure 5.4 Annual vertical profiles (top) and depth-time surface (bottom) of dissolved oxygen from simulation 4.



Run: 05 (1)
Channel depth = 12.18m
Oxygen fluxes = 0.1, 0.0035, 0.007
Start (mm/dd) = 01/16

16:41 Sep 13, 1990

Figure 5.5 Annual vertical profiles (top) and depth-time surface (bottom) of dissolved oxygen from simulation 5.

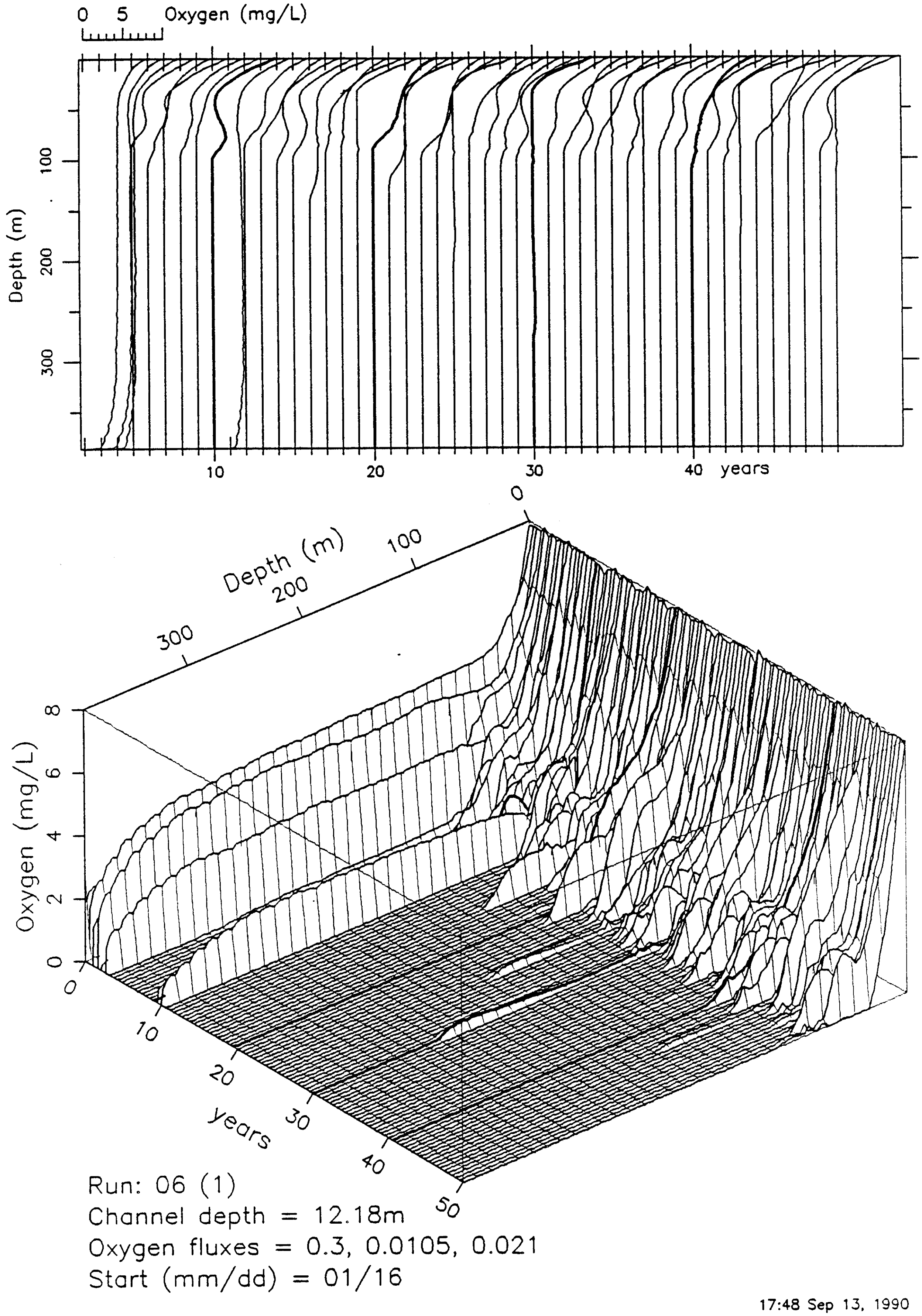


Figure 5.6 Annual vertical profiles (top) and depth-time surface (bottom) of dissolved oxygen from simulation 6.

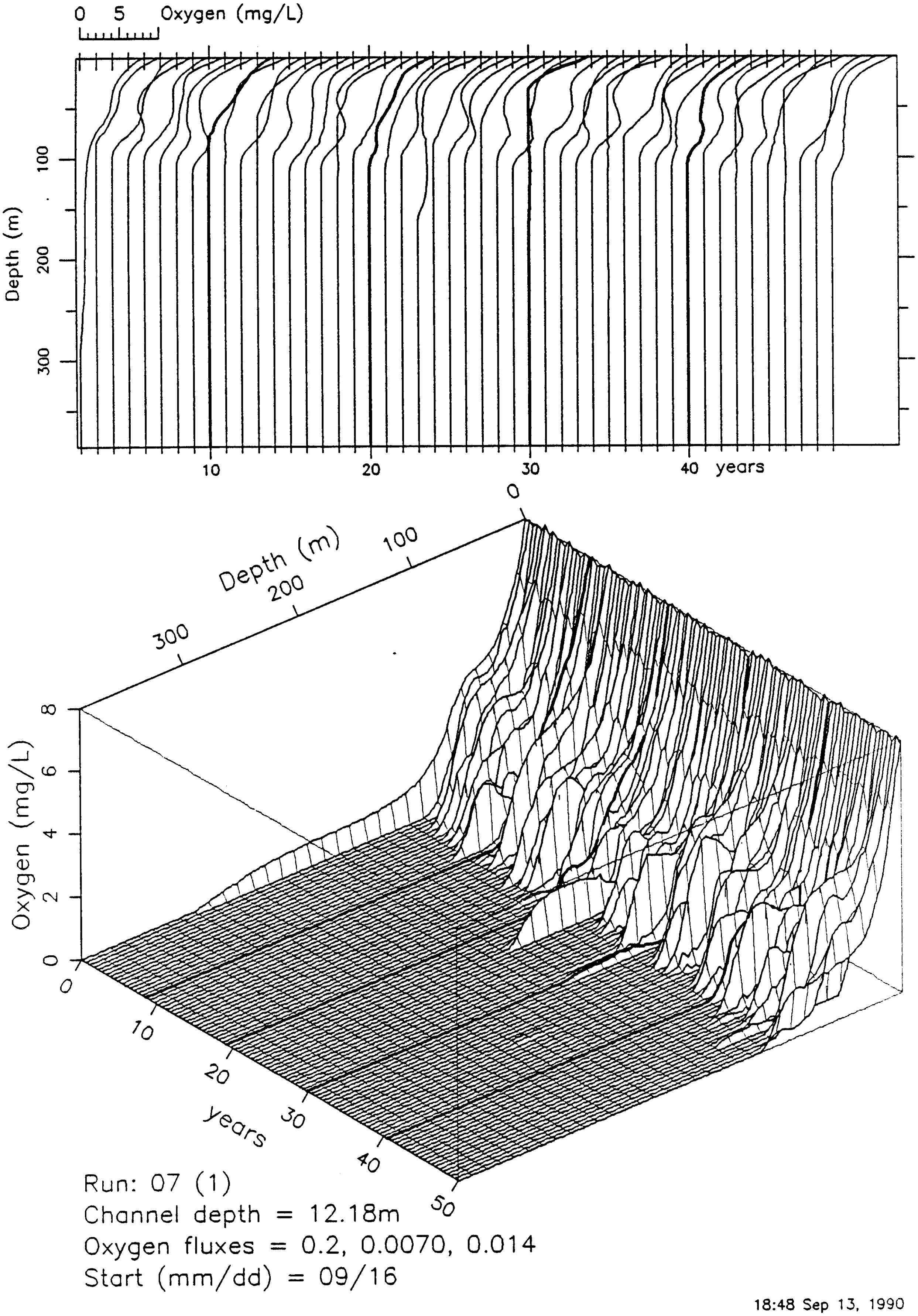


Figure 5.7 Annual vertical profiles (top) and depth-time surface (bottom) of dissolved oxygen from simulation 7.

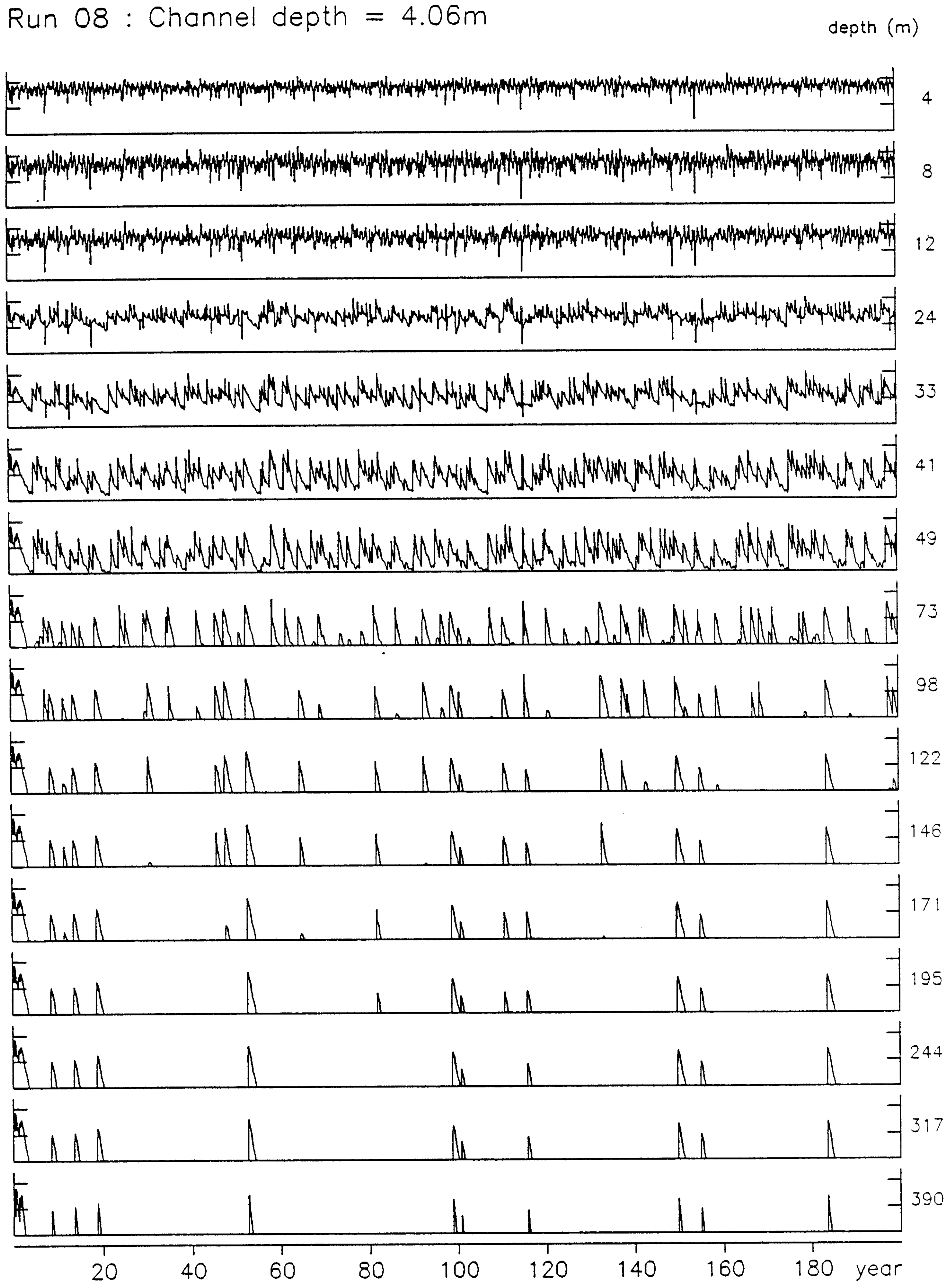


Figure 5.8 Time-series of dissolved oxygen at various depths from 200 year simulation 8.

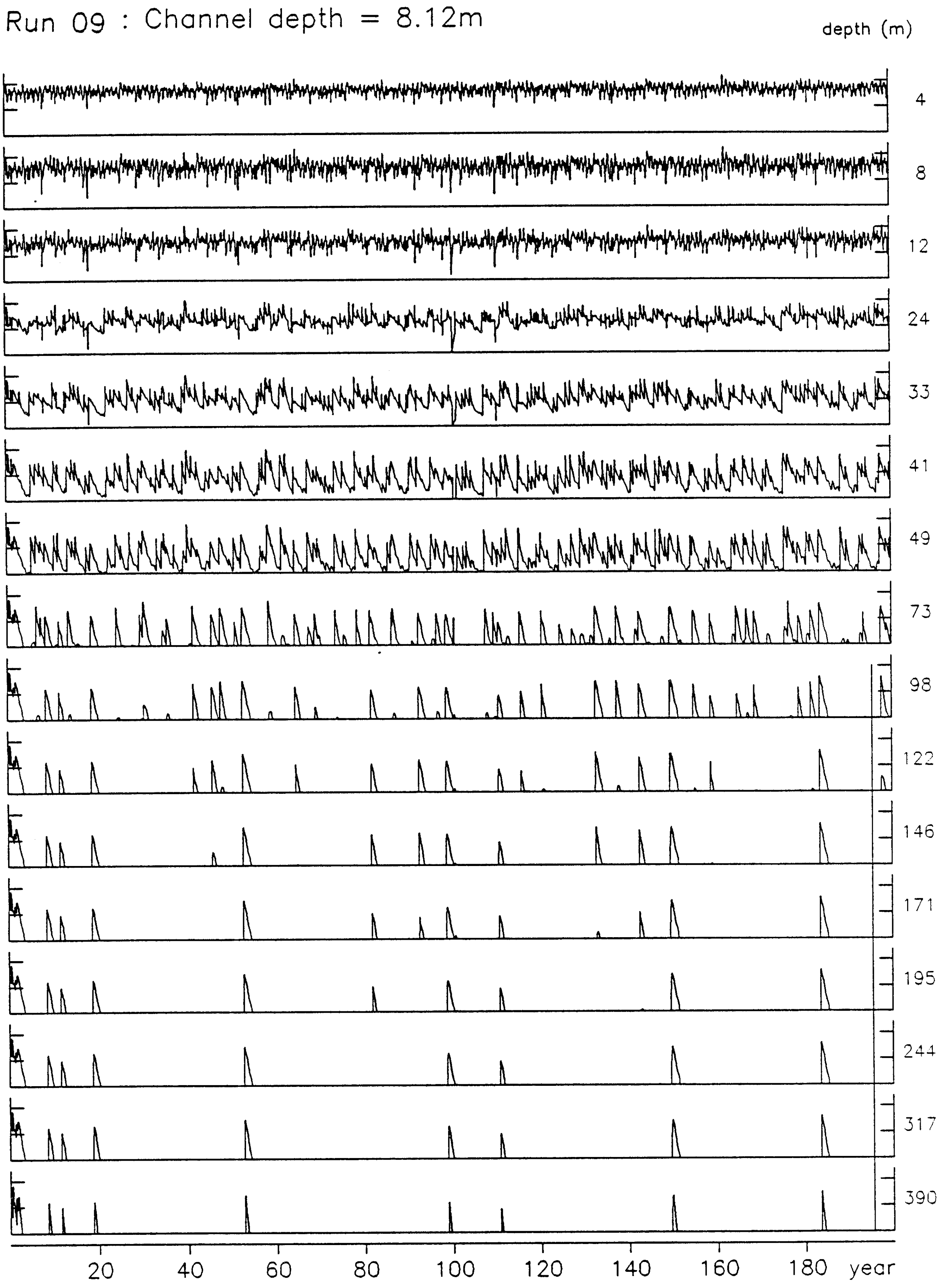


Figure 5.9 Time-series of dissolved oxygen at various depths from 200 year simulation 9.

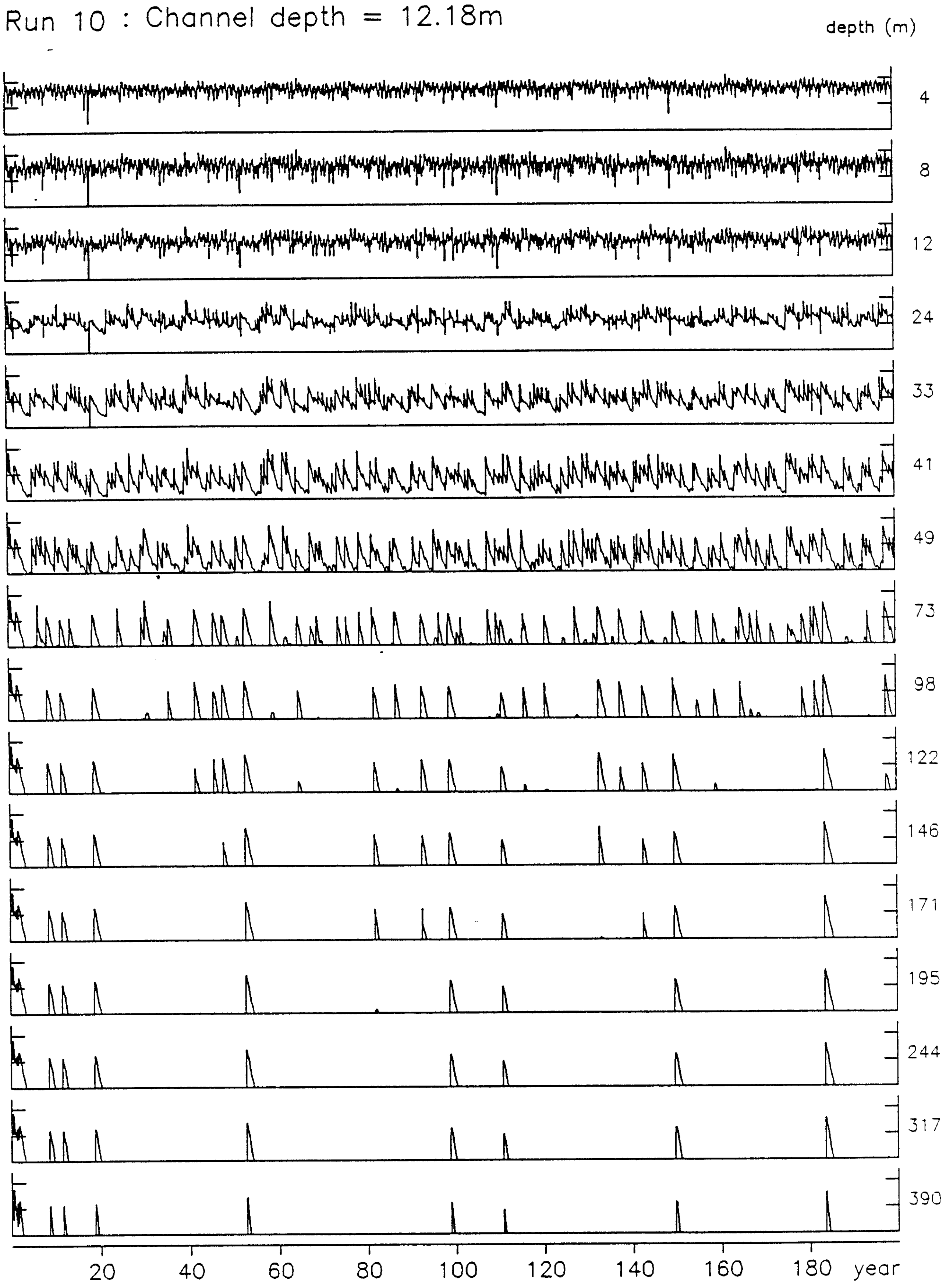


Figure 5.10 Time-series of dissolved oxygen at various depths from 200 year simulation 10.

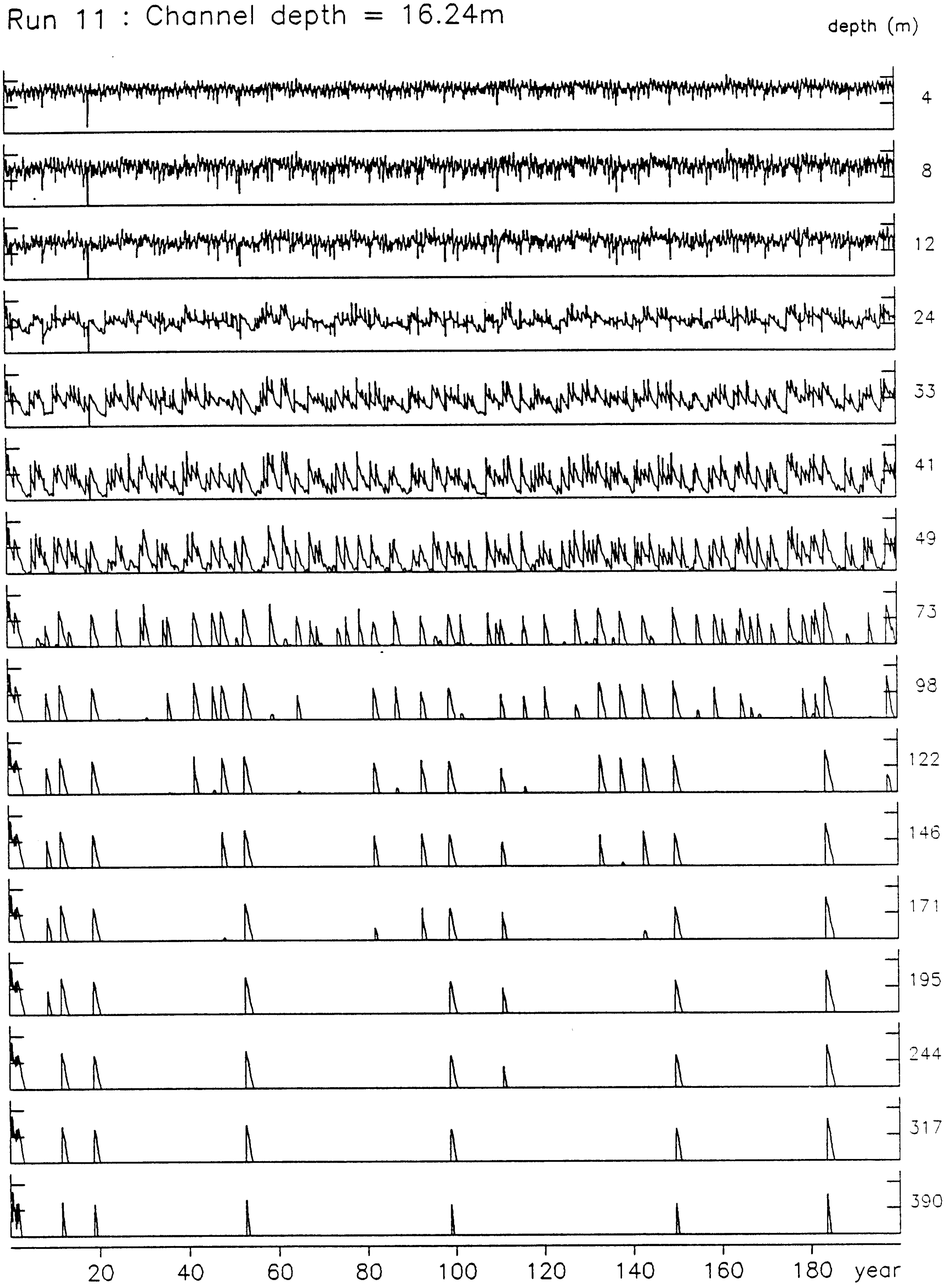


Figure 5.11 Time-series of dissolved oxygen at various depths from 200 year simulation 11.

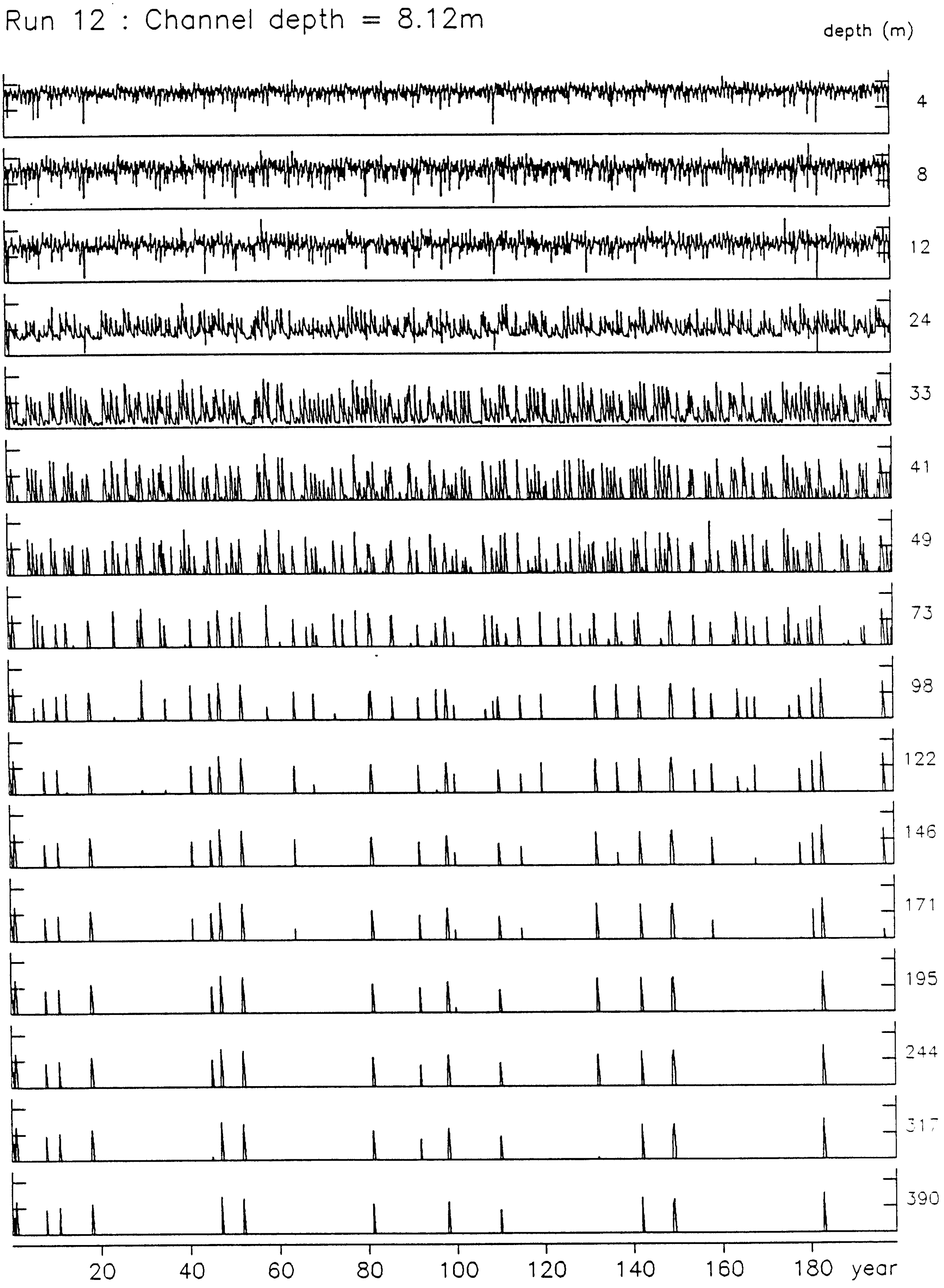


Figure 5.12 Time-series of dissolved oxygen at various depths from 200 year simulation 12.

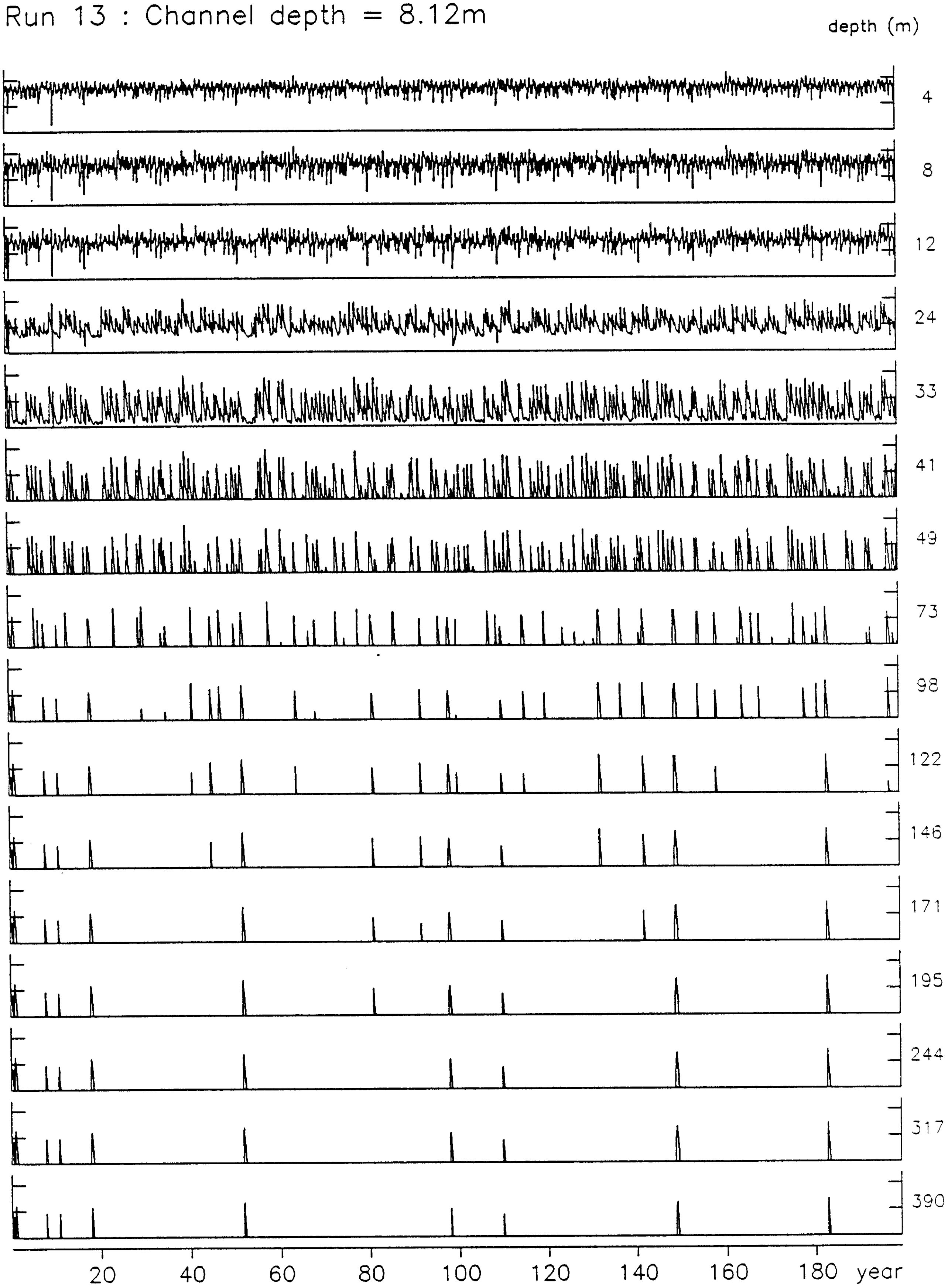


Figure 5.13 Time-series of dissolved oxygen at various depths from 200 year simulation 13.

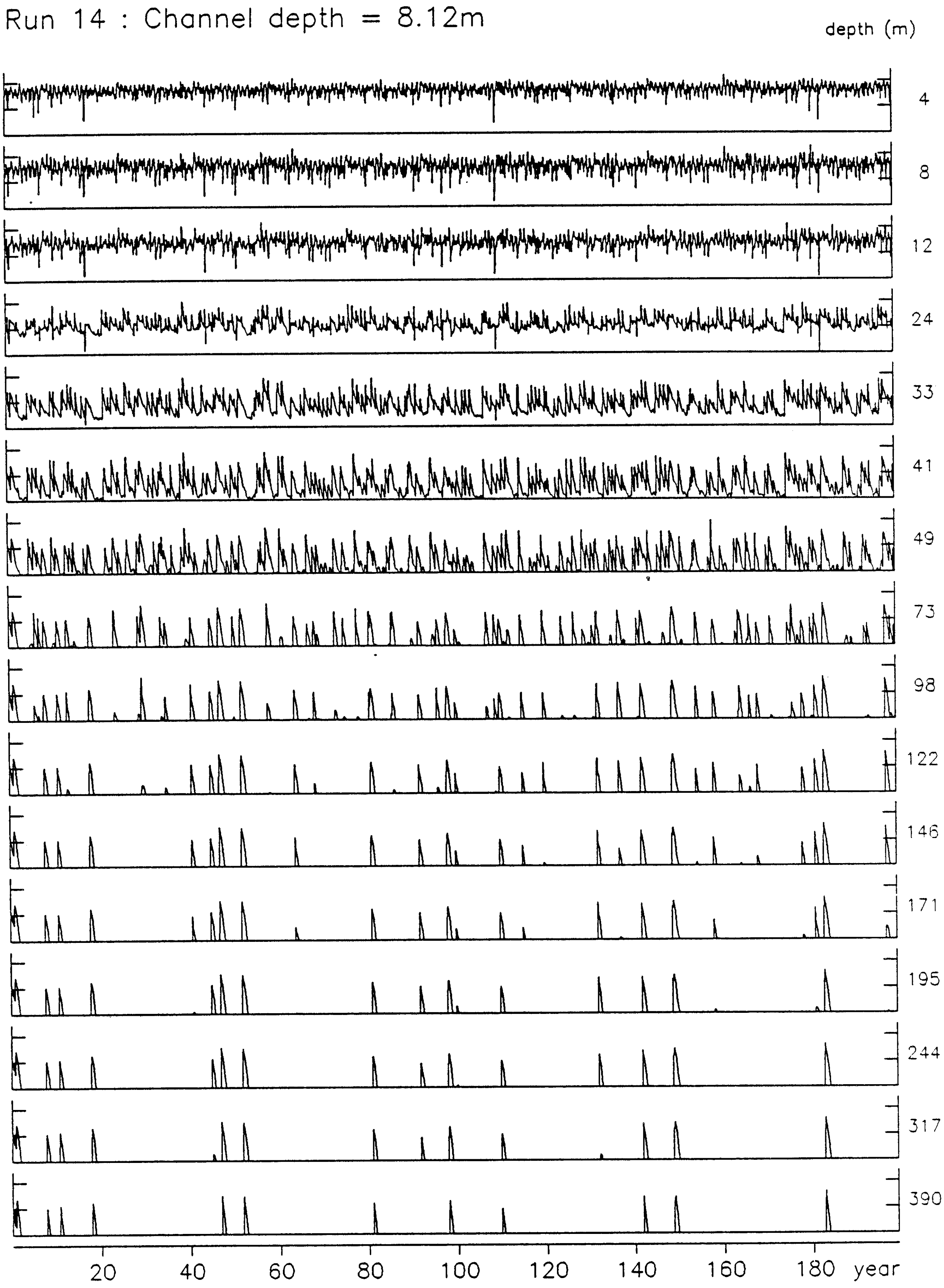


Figure 5.14 Time-series of dissolved oxygen at various depths from 200 year simulation 14.

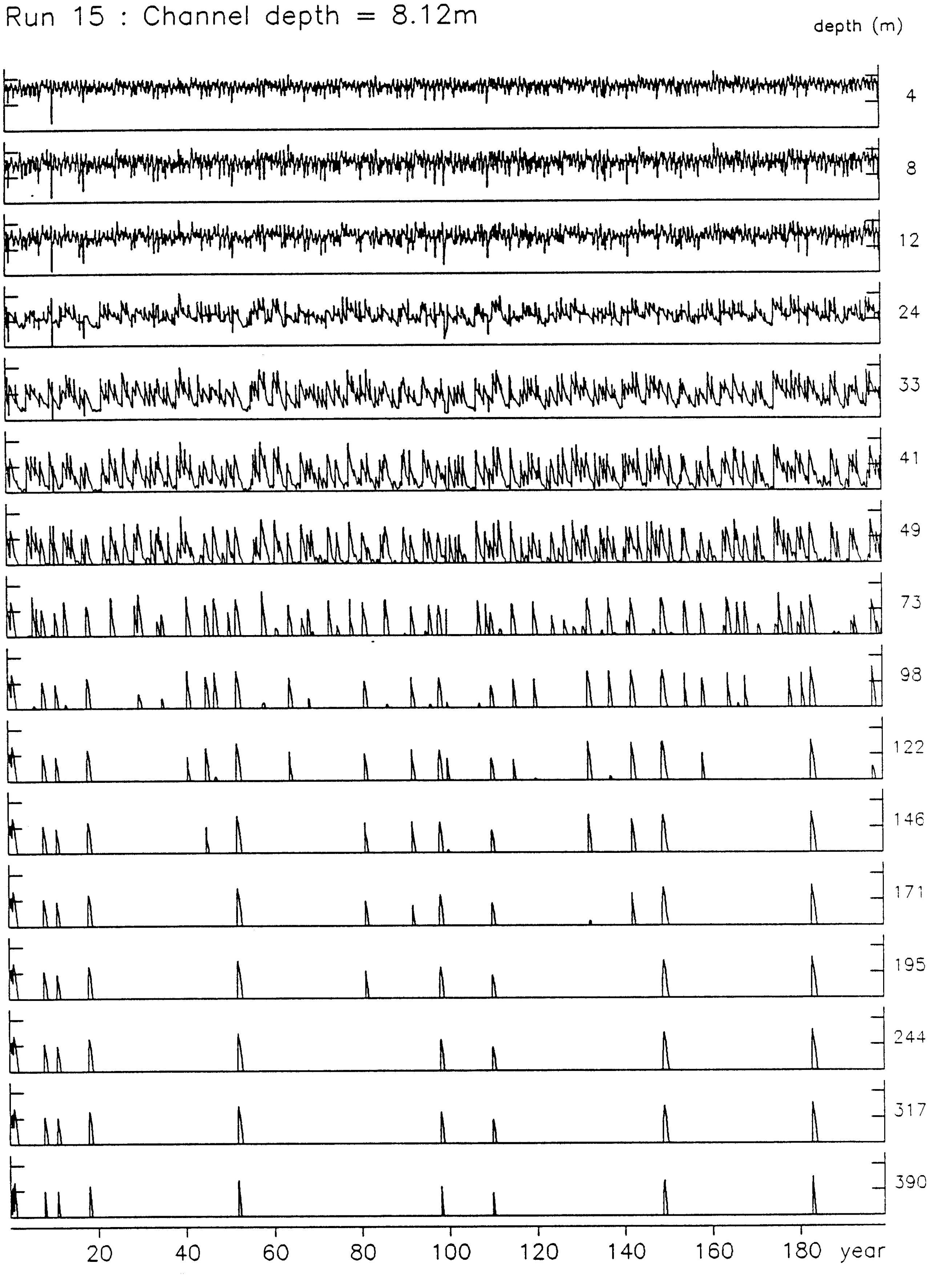


Figure 5.15 Time-series of dissolved oxygen at various depths from 200 year simulation 15.

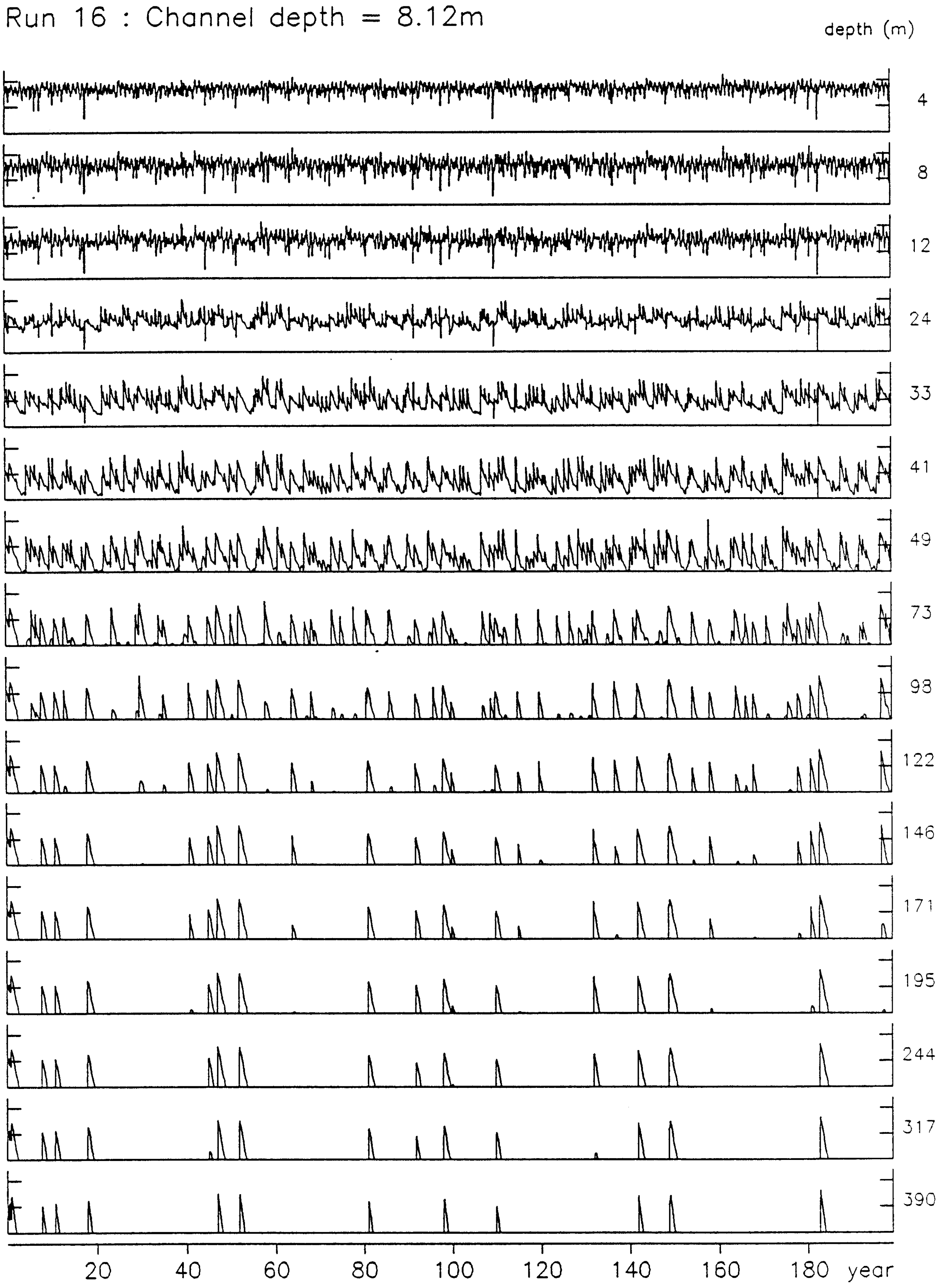


Figure 5.16 Time-series of dissolved oxygen at various depths from 200 year simulation 16.

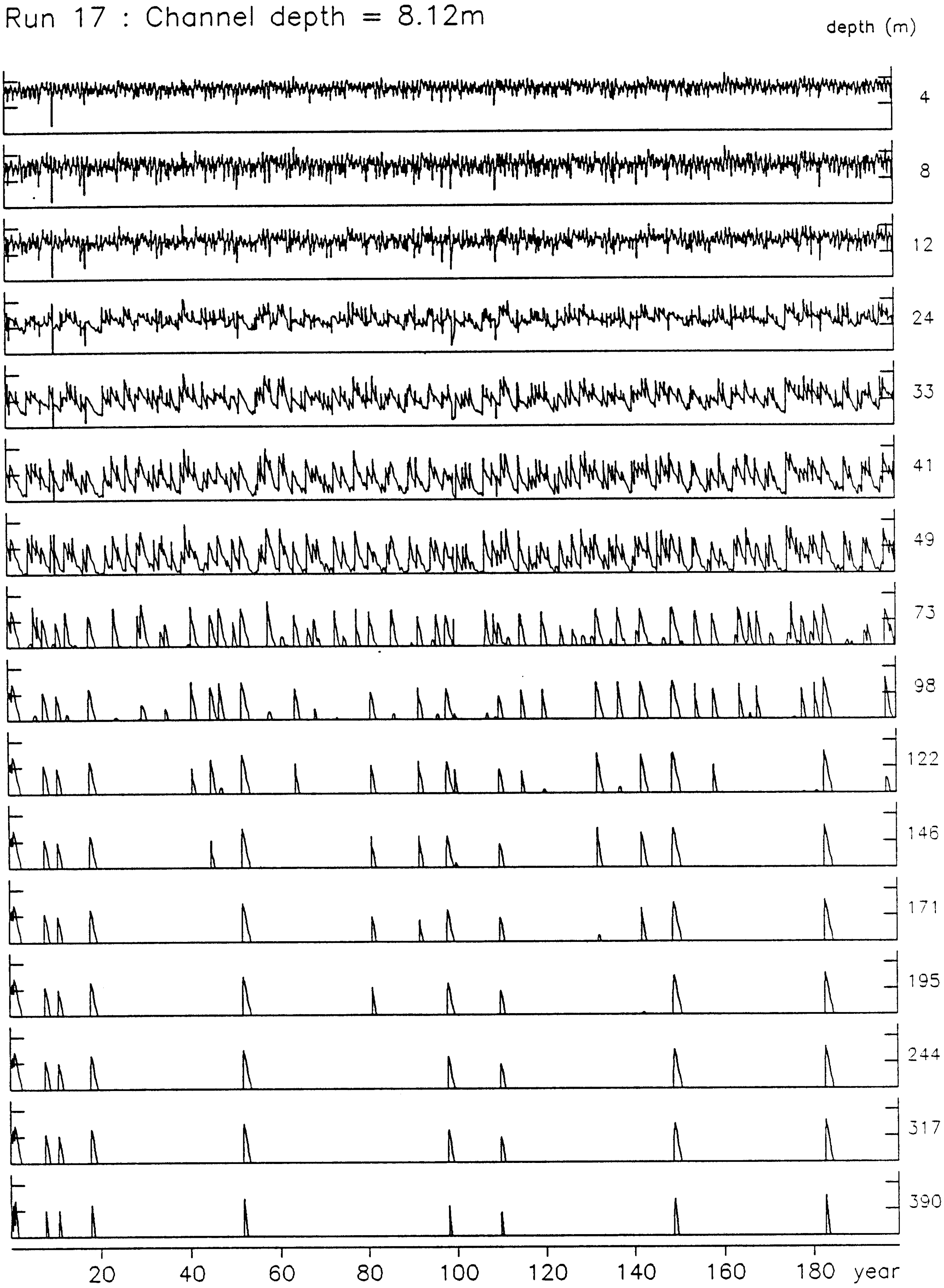


Figure 5.17 Time-series of dissolved oxygen at various depths from 200 year simulation 17.

mean oxygen level has decreased significantly; however, oxygenated conditions persist through most of the 200 year period. The frequency of spikes in the graph suggest that oxygen renewal occurs during most years. From the 75 m downward, protracted periods of anoxic conditions occur.

The sensitivity of the model results to enhanced turbulent mixing and very high oxygen depletion rates was investigated in runs 12 to 17. The following discussion of these results is based on visual inspection of Fig. 5.12 to 5.17, and an enumeration of overturning events which result in bottom oxygen concentrations greater than 5 mg/L and, occasionally, in surface water concentrations of less than 0.5 mg/L (Table 5.2).

In the six simulations included in Table 5.2, all used a channel depth of 8.13 m and initiated filling of the pit on October 28--the day during the first year which had the greatest water density in the channel. The bottom oxygen consumption rate was held fixed at 0.2 $g/m^2/d$, while three levels of in situ oxygen consumption were used. High, medium, and low levels of 0.050, 0.021, and 0.014 $g/m^3/d$ were used for the oxygen consumption rates during the high productivity time of the year. As before, these values were reduced by half during low productivity. Two runs were made at each level of oxygen consumption. The first scaled the vertical turbulent mixing coefficients that were calculated by the model by a factor of ten. The second used the normal values for these coefficients. Thus, runs 12, 14, and 16 correspond to greatly enhanced turbulent mixing.

The effect of enhanced mixing is reflected in the occurrence of 30 to 50% greater number of bottom renewal events, although the concentrations during coincident events are nearly the same. However, the effect on surface depletion is less clear. There are more events for the cases of high oxygen consumption (relative to runs using medium and low rates of oxygen demand) due to the upward mixing of oxygen depleted water to the surface from below. The oxygen distribution is insensitive to mixing rates over the prescribed range.

Elevated oxygen consumption rates cause a slight drop in the number of bottom renewal events, but not a marked change in the overall results. Generally, the oxygen distribution is insensitive to this range of consumption rates.

The details of renewal and depletion events may be examined in Fig. 5.18 to 5.20. Figure 5.18 shows the daily values of oxygen concentration from the first 14 years of simulation 15. Figures 5.19 and 5.20 each show 55 days from two events during this period. In Fig. 5.19 an influx of oxygenated water arrives at successively greater depths beginning at the start of event 1 until day 26 when it reaches the bottom. Prior to this arrival, the pit was anoxic from 50 m to the bottom. Over the following 14 days the anoxic water is evident at increasingly shallower depths, which eventually reach 8 m for a brief period. The waters at 4 m remain oxygenated during the entire event.

Event 2, shown in Fig. 5.20, is similar in its development to event 1; however, the depletion of oxygen in the near-surface waters is much more dramatic. Oxygen concentrations at 4 m remain low for about one week, reaching zero briefly during this time. At 24 m the water is anoxic for the same duration. By day 35 the entire water column has become oxygenated.

Table 5.2

Dissolved Oxygen Concentrations (mg/L) for Surface Depletion and Bottom Renewal Events from 200-Year Simulations

Surface Depletion (DO < 0.5 mg/L)

O_2 Uptake:	High		Medium		Low	
turb.mixing:	High	Low	High	Low	High	Low
Run No.:	12	13	14	15	16	17
Event (yy/mm)						
1/09	0.00	0.00	-	-	-	-
8/07	0.34	0.01	-	0.05*	-	0.06
11/08	-	0.38	-	0.38*	-	0.38
52/07	0.41	-	0.42	-	0.43	-
110/09	0.30	-	-	-	-	-
No. of events	4	3	1	2	1	2
Avg. interval (yr)	50.0	66.7	200.0	100.0	200.0	100.0

Bottom Renewal (DO > 5.0 mg/L)

O_2 Uptake:	High		Medium		Low	
turb.mixing:	High	Low	High	Low	High	Low
Run No.:	12	13	14	15	16	17
Event (yy/mm)						
1/04	-	-	5.51	-	-	6.40
1/10	6.71	6.61	7.13	7.08	7.29	7.26
8/08	-	-	5.49	-*	5.57	5.66
11/08	-	-	5.72	5.31*	5.78	5.37
8/11	6.16	6.24	6.39	6.45	6.44	6.50
47/09	7.67	-	7.77	-	7.80	-
52/08	7.21	7.03	7.56	7.38	7.64	7.47
81/10	5.95	-	6.12	-	6.16	-
98/11	6.41	6.11	6.63	6.29	6.70	6.33
142/09	6.89	-	7.09	-	7.13	-
149/10	7.02	7.14	7.41	7.47	7.50	7.55
183/08	8.07	7.81	8.30	8.06	8.32	8.12
No. of events	9	6	12	7	11	9
Avg. interval (yr)	22.2	33.3	16.7	28.6	16.7	22.2

*shown in detail in Fig. 5.19 and 5.20

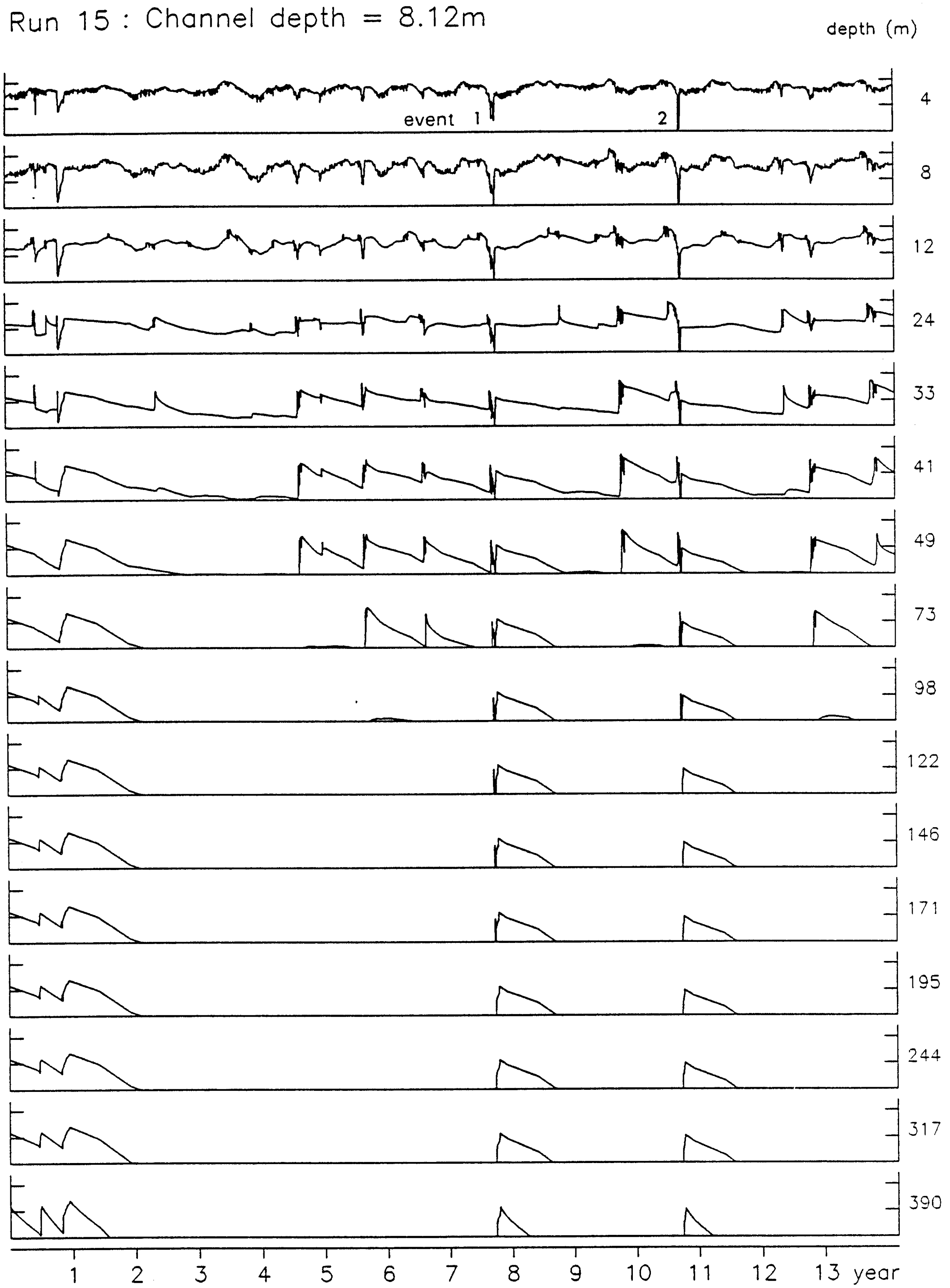


Figure 5.18 Daily oxygen concentrations at various depths from the first 14 years of simulation 15.

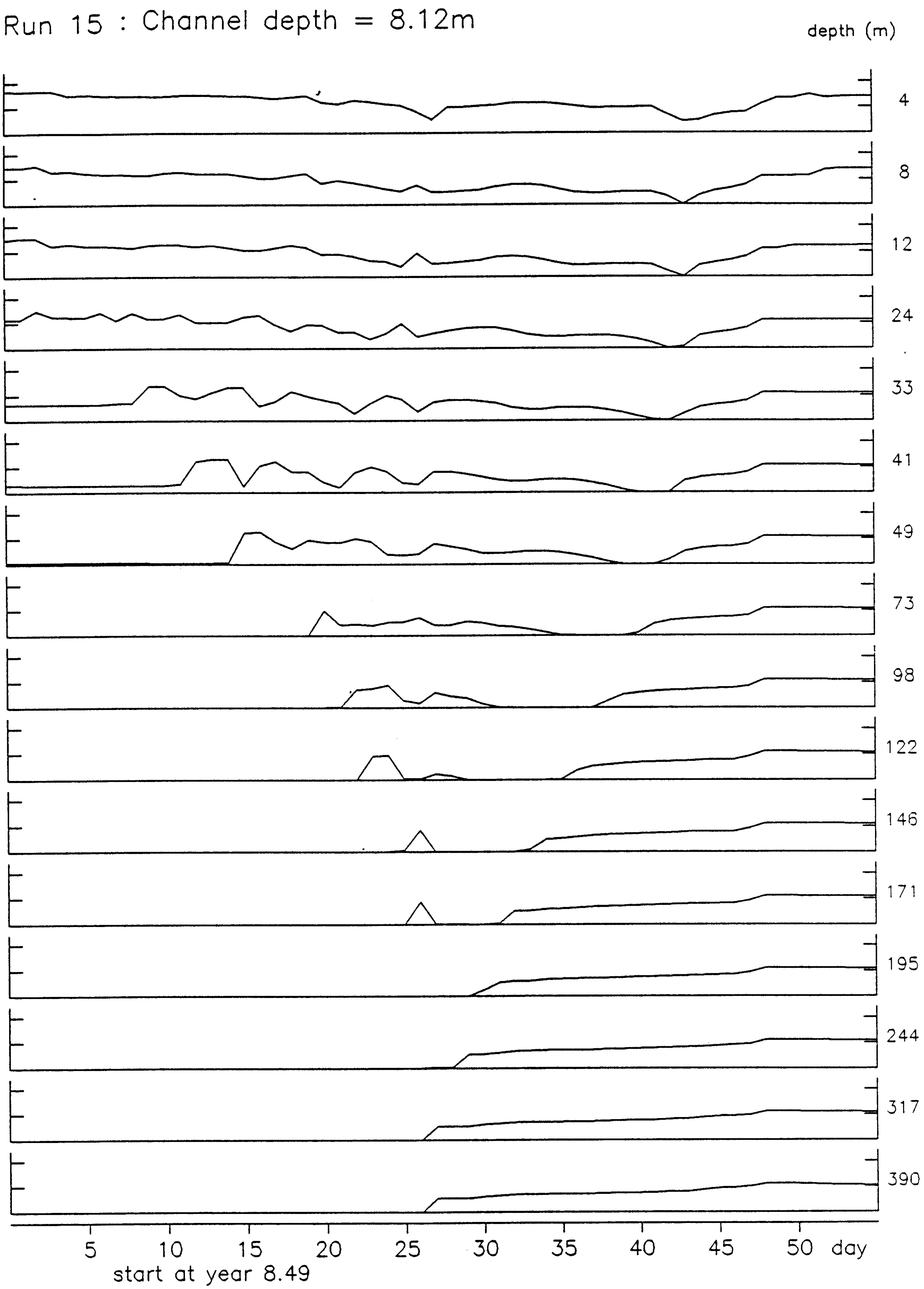


Figure 5.19 Renewal/depletion event 1 from 200 year simulation 15

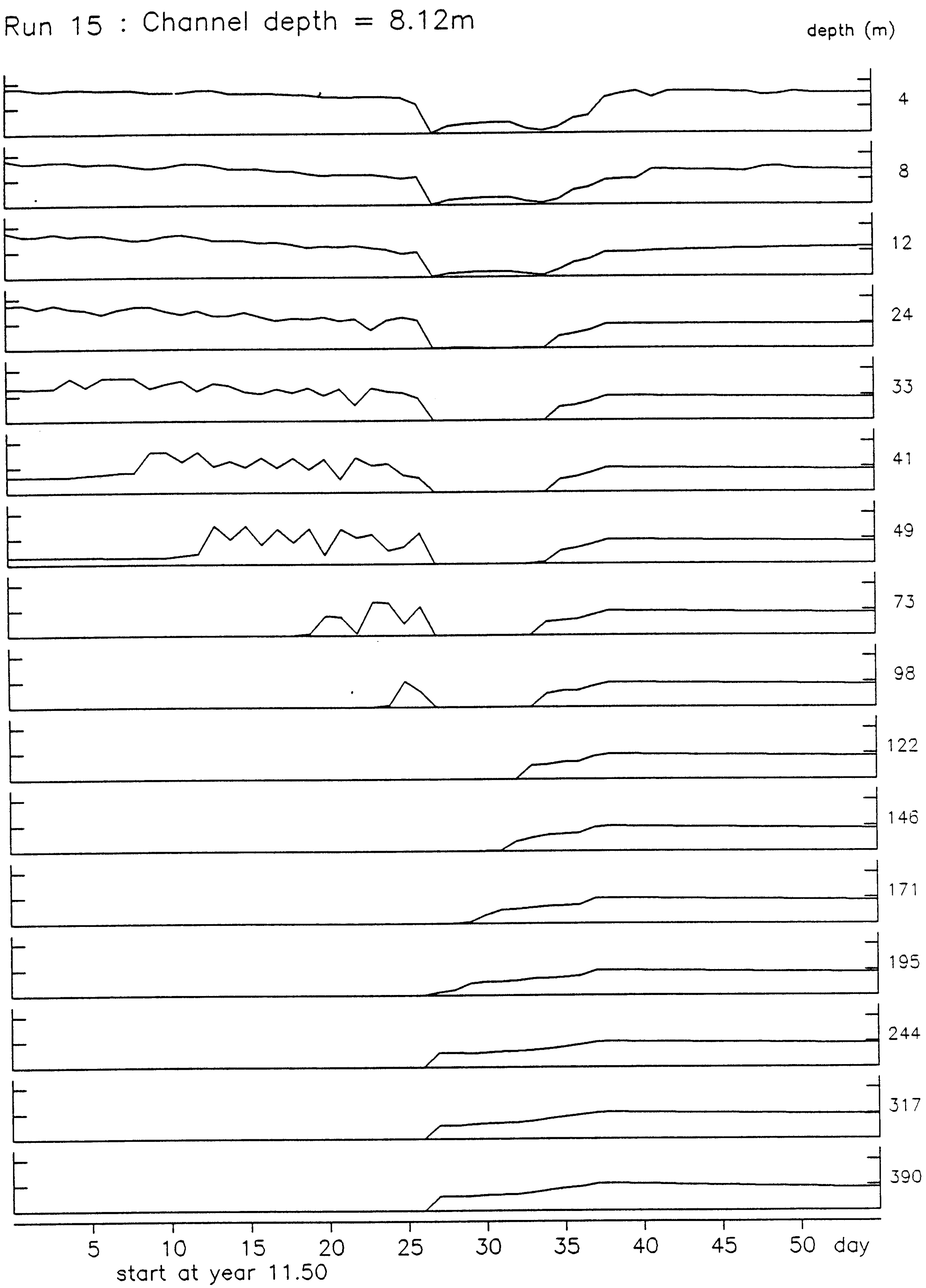


Figure 5.20 Renewal/depletion event 2 from 200 year simulation 15

6.0 CONCLUSIONS

(1) The dissolved oxygen level in the pit from the surface to a depth of about 25 m maintains a mean value above 5 mg/L. Below this depth the level decreases rapidly to a mean value near 0 mg/L at about 100 m.

(2) The primarily anoxic conditions that exist from 100 m to the bottom are perturbed by episodic intrusions of oxygenated water that occur, on average, every 16 to 33 years, elevating the oxygen level to above 5 mg/L at all depths. When they occur, these events take generally take place from August to November, although two April events were noted.

(3) Rare events--occurring from once to four times in 200 years--result in anoxic conditions from 4 m to the bottom of the pit. These events occur exclusively during summer, with surface anoxic conditions persisting for up to 10 days. Their occurrence coincides with extreme bottom renewal events which displace anoxic bottom waters upward to the surface.

(4) The final DO profiles are similar for channel depths between about 4 and 16 m; thus a shallow wide channel appears to be an acceptable alternative with no clear advantages associated with a deeper channel within the range of depths that were modelled.

(5) A channel area of 4000 ft^2 (372 m^2) yielded maximum currents of about 1.5 m/s for spring tides which are admissible for navigation. Water exchange between Rupert Inlet and the pit also achieves 90 to 95% of the tidal prism for the pit and thus there is little or no choking of flow in a channel of this area. A channel design of 160 ft wide by 25 ft deep would provide the same results and may meet certain construction criteria.

(6) Providing annual, periodic boundary data to the pit model results in a stable distribution of oxygen in the pit, that is, a distribution that exhibits annual variability, but which is constant from year to year.

(7) The final distribution of oxygen is not strongly dependent on the prescribed oxygen uptake rates within the ranges used for the simulations; that is: 0.1 to 0.3 g/m^2 for the benthic rate, 0.007 to 0.025 g/m^3 for the winter in situ rate, and 0.007 to 0.05 g/m^3 for the in situ rate during the six month period of high productivity. Higher oxygen consumption rates yielded more surface depletion events and slightly fewer bottom renewal events compared with moderate and low rates.

(8) The final distribution of oxygen is not strongly dependent on the value of the vertical turbulent mixing coefficient within the range of values employed. Values differing by a factor of 10 yielded results that were similar. 33 to 50% more bottom renewal events (DO greater than 5 mg/L) occurred when the higher values were used. The effect on surface depletion was not significant.

(9) The long-term (greater than 10 years) distribution of oxygen is also insensitive to the time during the year that the pit is filled. Beginning in early winter with minimum density water in the channel, about 10 years were required to reach the same steady state as occurs when the pit is filled during early fall with water of maximum density. The short term evolution of the pit (less than 10 years), however, is strongly affected by the time of year during which the pit is filled.

REFERENCES

Bo Pedersen, F., 1980. A Monograph on Turbulent Entrainment and Friction in Two-layer Stratified Flow. Institute of Hydrodynamics and Hydraulic Engineering, Tech. Univ. of Denmark, Series Paper No. 25.

Graham, R.J., 1963. Determination and Analysis of Numerical Smoothing Weights. NASA Tech. Rep. R-179.

Hodgins, S.L.M., 1977. An Improved Computational Method for the Shallow Water Wave Equations Based on the Leendertse (1967) Finite Difference Scheme. Vassdrags- og Havnelaboratoriet, Trondheim, SINTEF Report No. STF60 A77058.

Klein, L., 1962. Causes and Effects of River Pollution. Butterworth, London.

Leendertse, J.J., 1967. Aspects of a Computational Method for Long-period Water-wave Propagation. The Rand Corp. RM-5294-PR.

Svensson, T., 1979. Tracer Measurement of Mixing in the Deep Water of a Small, Stratified Sill Fjord. In Fjord Oceanography; ed. by Freeland, Farmer, and Levings; NATO Conference Series.

APPENDIX A:

Expected Chemical Evolution and Oxygen Balances in the Water Column of the Flooded Pit at Island Copper

Prepared by T.F. Pedersen, Ph.D.

EXPECTED CHEMICAL EVOLUTION AND OXYGEN BALANCES IN THE WATER COLUMN OF THE FLOODED PIT AT ISLAND COPPER

Introduction:

Flooding of the open pit with oxygenated seawater will be followed by a period of chemical adjustment in the water column - sediment continuum as a steady-state is established. This summary is based on the notion that exchange of water between the pit and Rupert Inlet will be restricted to a degree sufficient to establish permanently (or perhaps intermittently) anoxic conditions in "Island Inlet", similar to those seen in Lake Nitinat (Vancouver Island) or Framvaren (southern Norway). The roles of the oxygen demand in both the sediments and water column will be briefly considered, and the chemical dynamics of the sulphate - sulphide - iron sulphide system described. No attempt will be made to insert the reaction sequence into a chronological framework.

Oxygen Consumption and Dissolved Sulphide Generation - Theory

In both sediments and natural waters, reactive organic matter is degraded by a bacterial flora that derives its metabolic energy requirements by oxidizing the organic material. Such oxidation proceeds via a series of overlapping, enzyme-mediated electron-transfer reactions in which the thermodynamically-unstable reduced carbon compounds serve as electron donors and various oxidants act as terminal electron acceptors as degradation proceeds. The reaction sequence (Table 1) follows an order which is determined by net free energy yield, with aerobic oxidation, the highest-yield reaction, preceding (in thermodynamic order) denitrification, manganese and iron oxyhydroxide reduction, sulphate reduction, and methanogenesis (CO_2 reduction) (Froelich et al., 1979). Note that the various reactions are mediated by different bacterial communites (e.g. aerobes, nitrate reducers, sulphate reducers, and methanogens).

In a system that is essentially isolated from the atmosphere, such as deep water in a fjord or flooded open pit, bacterial consumption of O_2 may exhaust the oxygen content initially present, and anoxic conditions will be established, in which (in order) nitrate may be quantitatively reduced, manganese and iron oxyhydroxides dissolved, and hydrogen sulphide

Table 1. Oxidation reactions of sedimentary organic matter, listed in order of the free energy yields shown, from Froelich et al. (1979, and references therein). The free energy yields are presented as kJ per mole of CH_2O oxidized, and the organic matter stoichiometry chosen is equivalent to the Redfield ratio for marine plankton.

1. **Aerobic oxidation**: $\Delta G° = -475$ kJ/mol

$$(CH_2O)_{106}(NH_3)_{16}(H_3PO_4) + 138\ O_2 = 106\ CO_2 + 16\ HNO_3 + H_3PO_4 + 122\ H_2O$$

2. **Nitrate reduction** (denitrification): $\Delta G° = -448$ kJ/mol

$$(CH_2O)_{106}(NH_3)_{16}(H_3PO_4) + 84.8\ HNO_3 = 106\ CO_2 + 42.4\ N_2 + 16\ NH_3 + H_3PO_4 + 148.4\ H_2O$$

3. **Manganese oxide reduction**: $\Delta G° = -349$ kJ/mol

$$(CH_2O)_{106}(NH_3)_{16}(H_3PO_4) + 236\ MnO_2 + 472\ H^+ = 236\ Mn^{2+} + 106\ CO_2 + 8\ N_2 + H_3PO_4 + 366\ H_2O$$

4. **Iron oxyhydroxide reduction**: $\Delta G° = -114$ kJ/mol

$$(CH_2O)_{106}(NH_3)_{16}(H_3PO_4) + 424\ FeOOH + 848\ H^+ = 424\ Fe^{2+} + 106\ CO_2 + 16\ NH_3 + H_3PO_4 + 742\ H_2O$$

5. **Sulphate reduction**: $\Delta G° = -77$ kJ/mol

$$(CH_2O)_{106}(NH_3)_{16}(H_3PO_4) + 53\ SO_4^{2-} = 106\ CO_2 + 16\ NH_3 + 53\ S^{2-} + H_3PO_4 + 106\ H_2O$$

6. **Methanogenesis** (fermentation): $\Delta G° = -70$ kJ/mol

$$(CH_2O)_{106}(NH_3)_{16}(H_3PO_4) = 53\ CO_2 + 53\ CH_4 + 16\ NH_3 + H_3PO_4$$

produced as a product of sulphate reduction. In cases where the oxidant demand is extremely high, and the provision of oxidants to the site(s) of organic matter degradation is strongly limited, sulphate-reducing bacteria will deplete all the SO_4^{2-}, and production of methane will follow. This occurs for example, in deep water in Powell Lake (southwestern B.C.) where all the sulphate in 11,000 year-old seawater has been exhausted, but abundant, fresh organic matter is available.

The reaction sequence can be viewed as a "biogeochemical rubber band" which is stretched or compressed depending on the relative balance between the demand for oxidants (largely a function of the input of reactive organic matter to a basin) and their supply: restricted renewal of deep water will clearly limit the oxidant supply. The "rubber band" applies equally to sediments, which should be viewed as the part of the biogeochemical continuum in a basin. In that context, the oxic-anoxic boundary can occur below the sediment-water interface, as it does in coastal sediments, or above it, as it does in basins where deep-water renewal is absent or limited. Note that because of diffusion and kinetic effects (none of the reactions shown in Table 1 are instantaneous), the reactions (and therefore the distributions of their products) shown in Table 1 can overlap each other to some extent (see schematic in Fig. 1). For example, nitrate reduction often commences before O_2 is entirely depleted. There is little overlap, however, between the aerobic and sulphate-reducing zones because molecular oxygen is highly toxic to sulphate-reducing bacteria, and conversely, H_2S is highly toxic to aerobes.

The concentration of dissolved sulphide in anoxic basins is typically less than should be present based on the amount of sulphate which has been reduced. This is because, under anoxic conditions, sulphide minerals will precipitate readily if both dissolved metals and sulphide ion are present in solution. Dissolved iron precipitates as relatively stable FeS_2 (pyrite) or metastable FeS in the presence of HS^-, which is the dominant dissolved sulphide species at the pH of seawater, via:

$$Fe^{2+} + HS^- = FeS + H^+ \qquad (1)$$

$$FeS + S^0 = FeS_2 \qquad (2)$$

$$\text{or} \quad Fe^{2+} + S_x^{2-} + HS^- = FeS_2 + S_{x-1} + H^+ \qquad (3)$$

$$\text{or} \quad Fe^{2+} + S^0 + H_2S = FeS_2 + 2H^+ \qquad (4)$$

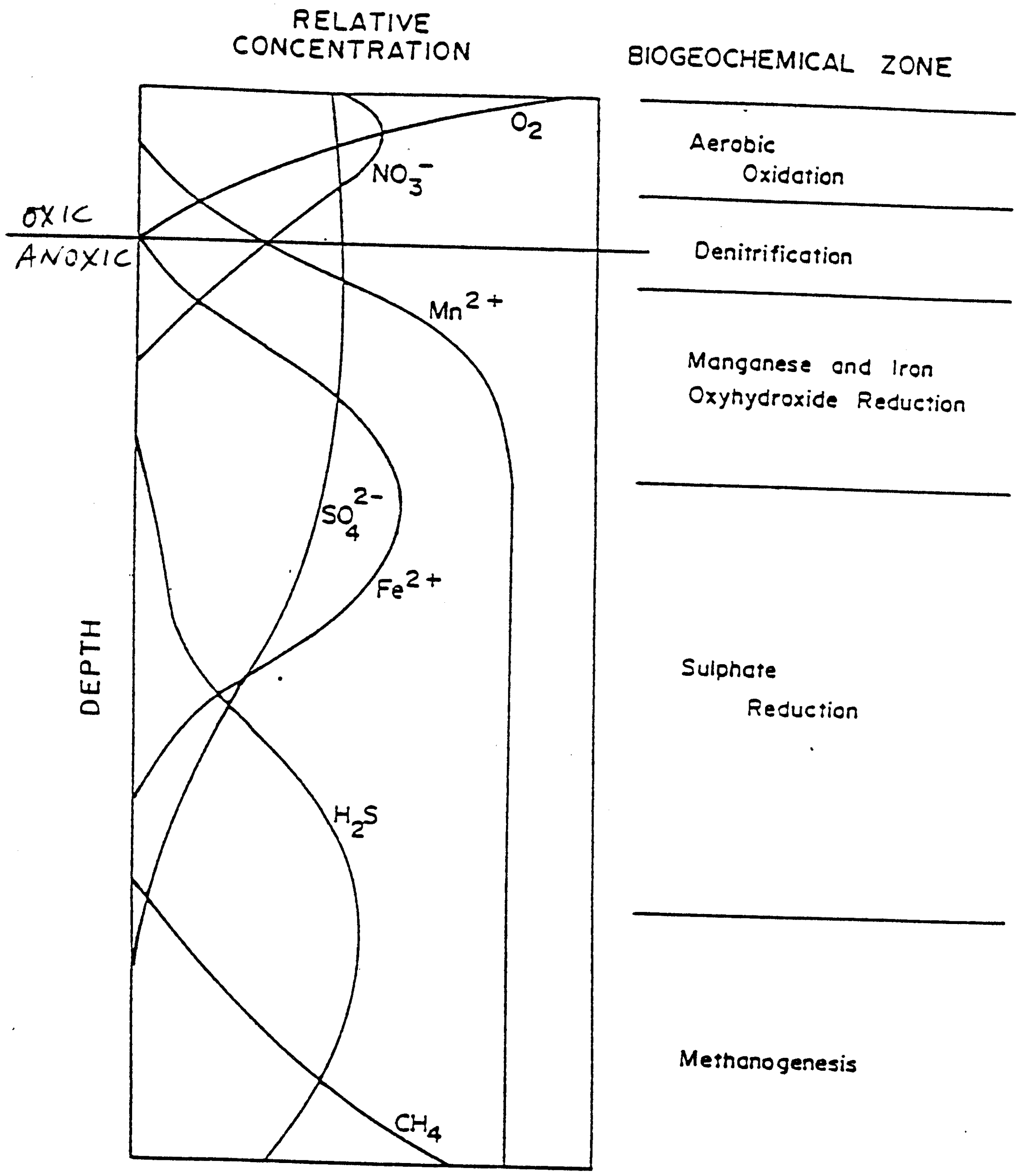


Figure 1. Simplified schematic showing the relative zonation of major oxidized and reduced species in a water or sediment column in which an aerobic zone overlies an anoxic zone

Note that FeS commonly reacts subsequently with elemental sulphur to form pyrite (Equation 2). The reactions shown above are responsible for the decrease of both sulphide and dissolved iron in the sulphate-reduction zone in the Fig. 1 schematic.

Because FeOOH is a minor but common constituent of lithogenous particulate matter, and because it is easily reduced in the absence of oxygen, settling terrigenous particles will release Fe^{2+} to solution at or just below the oxycline in an anoxic basin, thus supporting continuous precipitation of particulate iron sulphide phases. This phenomenon is observed, for example, in Powell Lake (K. Perry, unpublished data) and in Framvaren (Skei et al., 1989). Sulphide is also depleted from solution at or just above the oxycline by the abiotic precipitation of elemental sulphur (S°) as upward-diffusing HS^- is oxidized by O_2, via:

$$2H^+ + 2HS^- + O_2 = 2S^\circ + 2H_2O \qquad (5).$$

Sulphide oxidation thus establishes a chemical oxygen demand, as does the oxidation of upward-diffusing Fe^{2+} and Mn^{2+}, via:

$$2Fe^{2+} + 1/2O_2 + 4OH^- = 2FeOOH\ (s) + H_2O \qquad (6)$$

and $$2Mn^{2+} + O_2 + 4OH^- = 2MnO_2 + 2H_2O \qquad (7).$$

However, dissolved manganese and iron typically occur in much smaller concentrations (several to tens of µmols L^{-1}) than HS^- (up to several mmol L^{-1}), and are minor contributors to the chemical oxygen demand associated with abiotic oxidation.

It should be noted that under certain circumstances, upward-diffusing sulphide is also oxidized by certain strains of bacteria which can be resident at sharp oxyclines. In Framvaren, for example, and in at least one lake in south-central B.C. (Northcote and Hall, 1983) purple photosynthetic sulphide-oxidizing bacteria are abundant within a metre or so of the oxycline. Cell concentrations are so high in these examples that the water has a dark purple to magenta hue. Because they are photosynthetic, such bacteria can exist only in the photic zone. Other non-photosynthetic strains of bacteria are capable of oxidizing sulphide in the presence of O_2 in the dark (thus, depth is not a limitation).

Probable Biogeochemical Evolution of Anoxia in "Island Inlet"

Once flooded, a number of chemical changes will commence in the pit. The rates at which these phenomena will occur depend on a variety of factors, some of which will be constrained by the results of the Seaconsult model. Initial chemical boundary conditions include a fully-oxygenated water column and an essentially sediment-free bottom.

The input of allochthonous sediments (i.e. derived from outside the basin) to the new inlet is expected to be minor to negligible. This could change somewhat in the future depending on reclamation activities and the pace of soil development, but in the continuing absence of any significant stream inflow, the pit will remain a sediment-starved basin. Some particulate matter will be generated within the basin by biological production and will support a seasonally variable settling flux of slowly-settling organic-rich detritus and faecal pellets. By analogy with a number of B.C. fjords, the sedimentation rate in the pit could be expected to be on the order of one or two millimetres per year, given the predicted absence of fluvial detritus. Slumping from the terraced walls of the pit will also contribute to accumulation on the bottom to an unknown degree.

Oxygen will be consumed as a result of bacterial activity in the basin both in the water column and on the basin floor. Because the settling velocity of faecal pellets is quite fast (on the order of 100 m/day), organic matter will be delivered to the floor of the basin shortly after the spring bloom, and will support a benthic oxidant demand that will increase in intensity with time until some steady-state is reached. It is very difficult to estimate how long a period will be required to reach such a steady-state, but a few (?) to several years would probably be in the right range. Because the rate of replenishment of O_2 is expected to be low, anoxia will eventually be established in the basin. This will commence at the bottom, where the oxygen demand will be concentrated, and an oxic-anoxic boundary will propagate progressively upward.

In Saanich Inlet, the annual replacement of the anoxic deep water in the fall is followed by reestablishment of anoxia over a period of roughly six months (Anderson and Devol, 1973) which translates very crudely to a net oxygen consumption rate in Saanich deep water of 0.3 μmol L^{-1} day^{-1}. The deep water becomes anoxic after the spring bloom. This estimated consumption rate is comparable to that in sub-basins in Puget Sound where deep-water flushing is similarly restricted (Richards, 1965). Apparently, these basins receive essentially no new deep water following the autumn flushing event for a number of months, and in the case of Saanich, typically for a year.

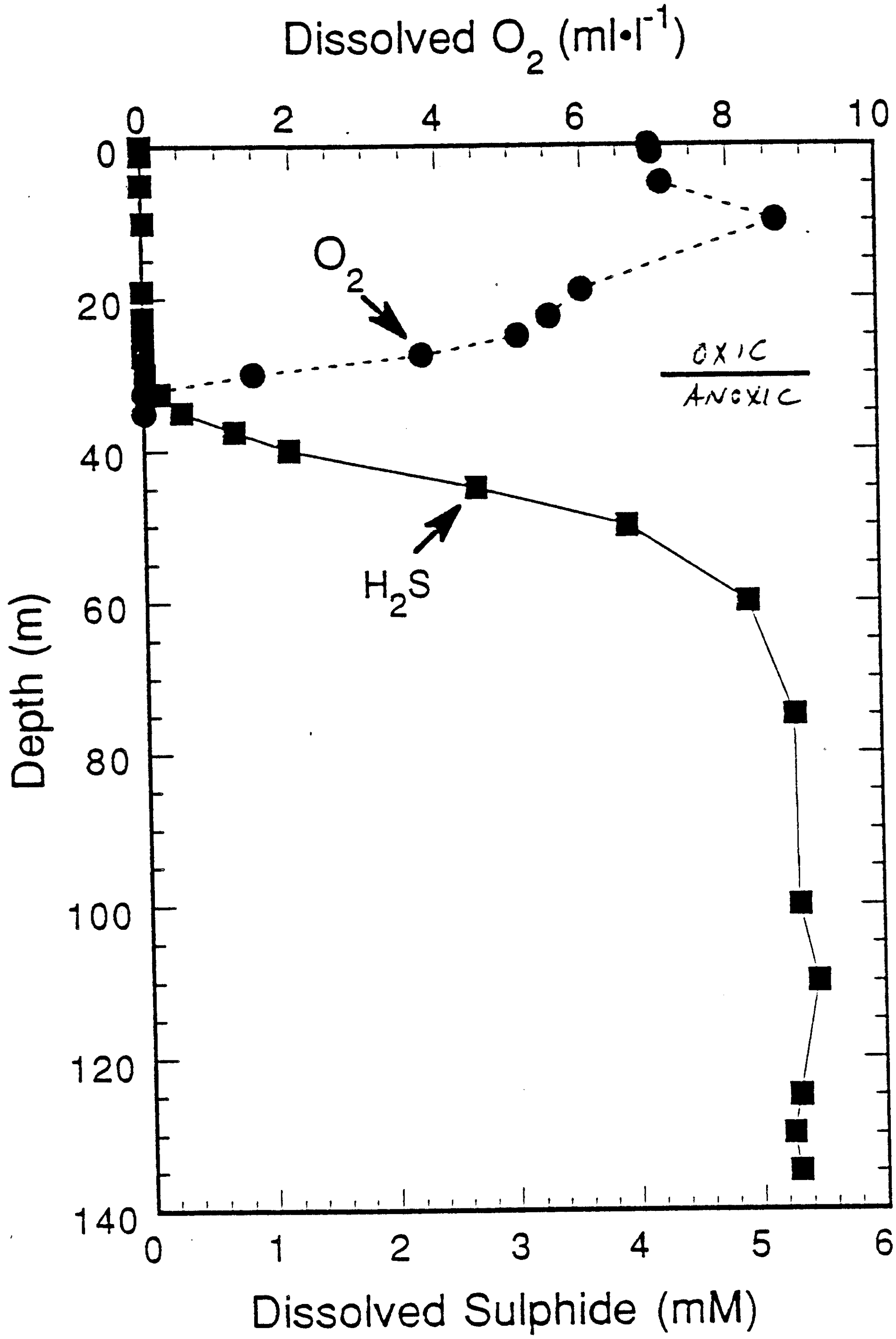
An oxygen consumption rate on the order of those described above would presumably be applicable to "Island Inlet" in the early stages following flooding, given a channel design which inhibits deep water renewal. However, it is important to note that Saanich Inlet and Puget Sound are floored by organic-rich sediments which have an inherently high oxygen demand. As discussed earlier, similar conditions will not be established in the flooded Island Copper pit for some time. Thus, a more conservative estimate of the O_2 consumption rate should best be employed in model calculations.

It might be possible to calculate the rate of upward propagation of the oxycline by using O_2 and H_2S distributions from a basin with roughly similar chemical characteristics to those expected to arise in the flooded pit. Sakinaw Lake (on the Sechelt Peninsula) is one such environment. The lake contains trapped seawater (like Powell Lake), but unlike the broad oxycline in Powell Lake, the sharp pycnoline in Sakinaw fosters an abrupt transition from oxygen-replete to H_2S-replete water at a depth of about 35 m (Fig. 2; K. Perry, unpublished data). Given a diffusion coefficient D for O_2 of 1.2×10^{-5} cm^2 sec^{-1} (at 4° C; Archer et al., 1988) and a concentration gradient ($\partial C/\partial Z$) of 30 µmol L^{-1} m^{-1} (estimated from the Sakinaw Lake data shown in Fig. 2, assuming a linear decrease in oxygen between 25 m [5 mL L^{-1}] and 32 m depth [0 mL L^{-1}]) and ignoring advection (this omission could be criticized, given the relatively shallow depth of the oxycline), the downward oxygen flux can be calculated from Fick's First Law, viz:

$$J = - D\,(\partial C/\partial Z) = - (1.2 \times 10^{-5}\ \mathrm{cm^2\ sec^{-1}})(30 \times 10^{-5}\ \mu\mathrm{mol\ cm^{-4}})$$

$$= \mathbf{3.1\ \mu mol\ m^{-2}\ day^{-1}}.$$

Because at steady-state the downward flux of oxygen balances the oxygen supply required to oxidize all the upward-diffusing reduced species (primarily HS^- and dissolved Fe and Mn), this flux can be used to characterize quantitatively the oxygen demand of the upward-moving, essentially planar, "reduction front". The calculated flux is probably an underestimate, given the assumption of control only by molecular diffusion. Nevertheless, this



Sakinaw Lake

Figure 2. Distribution of dissolved oxygen and H_2S in the Sakinaw Lake water column. Data from K. Perry (with permission).

empirically-constrained flux should be potentially useful as an input to the model.

References

Anderson, J.J. and A.H. Devol (1973). Deep water renewal in Saanich Inlet, an intermittently anoxic basin. Est. Coast. Mar. Sci. 1, 1-10.

Archer, D., S. Emerson, and C.R. Smith (1988). Direct measurement of the diffusive sublayer at the deep sea floor using oxygen microelectrodes. Unpublished ms.

Froelich, P.N. et al. (1979). Early oxidation of organic matter in pelagic sediments of the eastern equatorial Atlantic. Geochim. Cosmochim. Acta 43, 1075-1090.

Northcote, T.G. and K.J. Hall (1983). Limnological contrasts and anomalies in two adjacent saline lakes. Hydrobiologia, 105, 179-194.

Richards, F.A. (1965). Anoxic basins and fjords. In: Chemical Oceanography, Vol. 1, 1st Edition (eds. J.P. Riley and G. Skirrow), Academic Press. pp. 611-645.

Skei, J. (1986). The Biogenchemistry of Framvaren. Datareport 1931-1985. Norwegian Institute for Water Research (NIVA) Report F-80400, 256 pp.

APPENDIX B: A Stochastic Model for Non-periodic Boundary Conditions for the Pit Model.

A STOCHASTIC MODEL FOR NON-PERIODIC BOUNDARY CONDITIONS

Representative long-term boundary conditions, which incorporate interannual and higher frequency variability, were synthesized for each water quality parameter based on a statistical analysis of 17 years of monthly water quality data from Rupert Inlet.

Measured vertical profiles of dissolved oxygen, salinity and temperature were first numerically integrated to the depth of the channel being used in each simulation. The resulting integrated data were then subsampled using linear interpolation in time to yield time-series of daily values covering the entire 17 year sampling period. The time-series data sets spanning the period from Jan 1, 1972 to Jan 1, 1989 were then Fourier transformed.

All Fourier components corresponding to periods of less than 365.25 days were set to zero and an inverse Fourier transform was performed to yield an interannual mean. A residual time-series was then calculated by subtracting this mean from the original, daily values.

An autocorrelation function for the residual series, $\{X(i): i=1,2,\ldots,N\}$, using 15 day lags was then evaluated for the first 40 lags (600 days). This function is given by

$$R(m) = C(m)/C(0) \tag{B.1}$$

where the autocovariance function, C(m), for lag m is given by

$$C(m) = N^{-1} \sum_{i=1}^{N-m} X(i+m) * X(i) \tag{B.2}$$

A linear autoregressive stochastic model corresponding to lag m is defined for time t by

$$X'_t = a_1 \cdot X'_{t-1} + a_2 \cdot X'_{t-2} + \ldots + a_m \cdot X'_{t-m} + Z_t \tag{B.3}$$

where Z_t is a Gaussian random variable with zero mean and variance σ^2, and the a_j are coefficients determined from the solution of the linear system of equations

$$C(j) = a_1\, C(j-1) + a_2\, C(j-2) + \ldots + a_m\, C(j-m) \tag{B.4}$$

for $j = 1, 2, \ldots, m$. The variance σ^2 is estimated using

$$\sigma^2 = S(a_1,\ldots,a_m) / (N-2m-1) \tag{B.5}$$

and

$$S(a_1,\ldots,a_m) = (N-m)\cdot(C(0)-a_1\, C(1)-\ldots-a_m\, C(m)) \tag{B.6}$$

The model having the minimum residual variance σ^2 was then selected and (B.3) was used to synthesize a 200 year time-series of residual values.

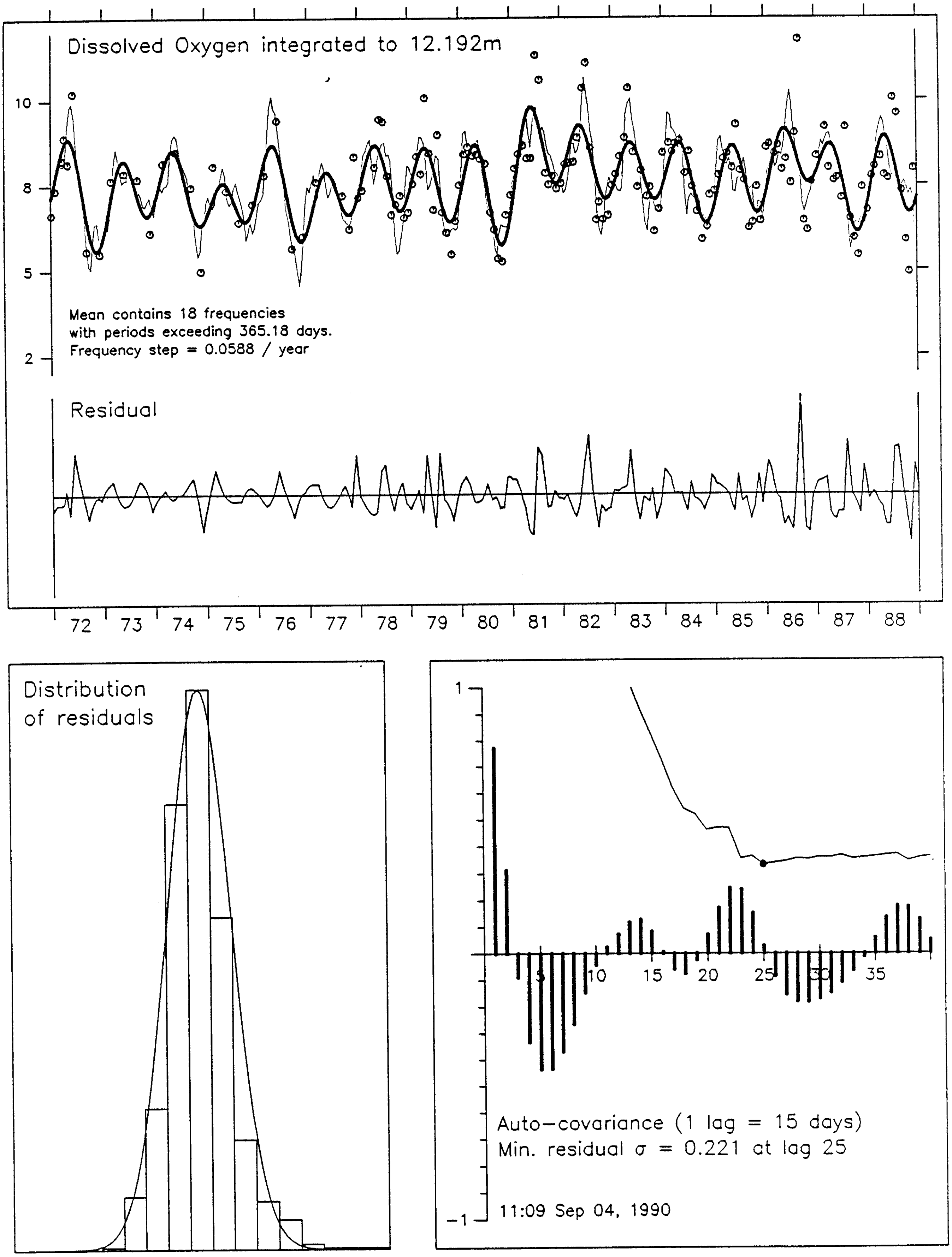
These residuals were added to the interannual mean to yield a time-series of boundary data. For this purpose, the mean time-series was assumed to be periodic with a 17 year period.

Figures B.1 to B.3 illustrate the modelling process for dissolved oxygen, salinity and temperature for a 12.19 m (40 ft) deep channel. The top panel in each figure shows the depth integrated values (open circles), the interannual mean (bold line), and a synthetic time-series for that period (normal line). The residual series representing the difference between the depth integrated values and the interannual mean is plotted below in the same panel.

The lower left panel contains a histogram for the distribution of the residual series about zero together with a Gaussian curve having the same variance as this series. A close match between the two indicates that the residual series is stationary and normally distributed, which are necessary criteria for applying the statistical analysis. The lower right panel shows the autocorrelation function of the residual series evaluated for the first 40 lags (vertical bars), together with the residual standard deviation, s, for the autoregressive model corresponding to each of these lags (solid line). A solid circle marks the minimum variance, and corresponds to the lag number of the model used to synthesize the boundary time-series.

A sample synthetic time-series has been calculated for the sampling period and plotted on the upper panel.

The synthesized time-series are not expected to reproduce the original measurements, rather they exhibit the same statistical behaviour as the the vertically integrated data.


Dissolved Oxygen integrated to 12.192m

Mean contains 18 frequencies
with periods exceeding 365.18 days.
Frequency step = 0.0588 / year

Residual

Distribution
of residuals

Auto–covariance (1 lag = 15 days)
Min. residual σ = 0.221 at lag 25

11:09 Sep 04, 1990

Figure B.1 Stochastic model results for dissolved oxygen for a 12 m deep channel.

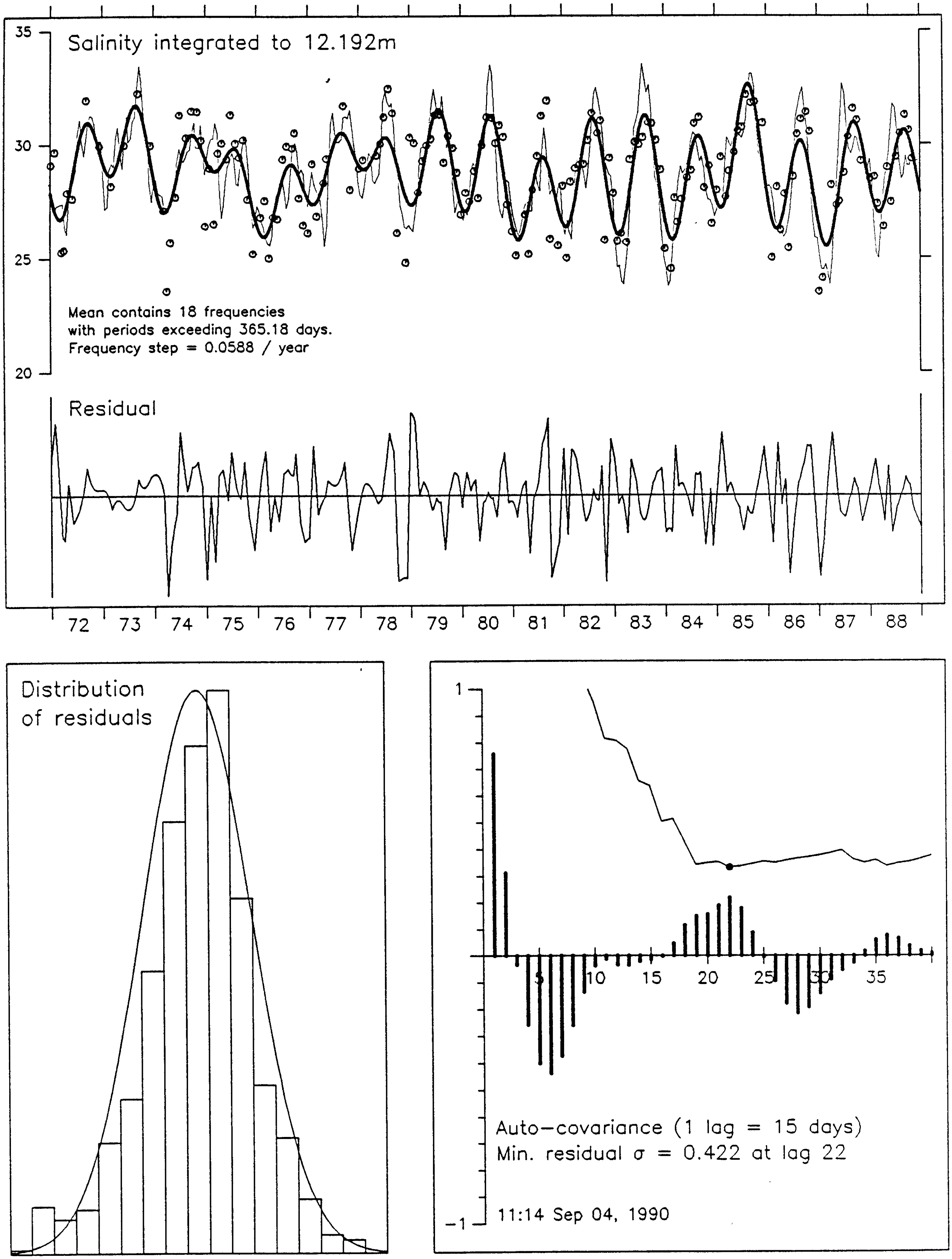


Figure B.2 Stochastic model results for salinity for a 12 m deep channel.

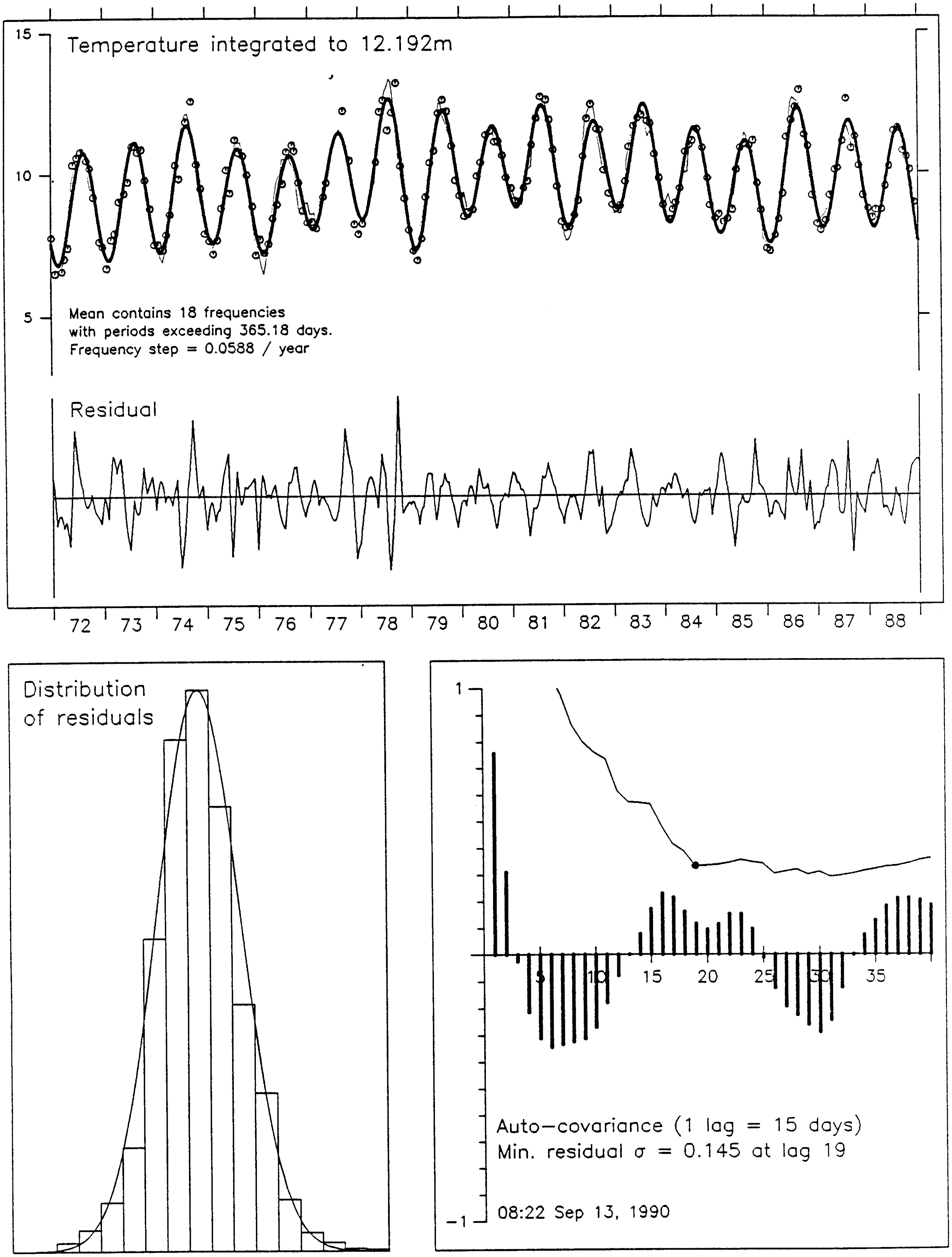


Figure B.3 Stochastic model results for temperature for a 12 m deep channel.

Appendix 2

Island Copper Mine

NORTH WEST DUMP STUDY

STAGE REPORT 1

SUBMITTED TO:

Island Copper Mine, Port Hardy

SUBMITTED BY:

Department of Mining and Mineral Process Eng.
University of British Columbia
Vancouver, B.C.

April,1990

EXECUTIVE SUMMARY

The North West Dump (NWD) at BHP-Utah Mines Ltd., Island Copper Mine is a small isolated waste rock dump well suited for acid production study. Up to the present, works that have been completed on the North West Dump project include drilling of seven monitoring wells plus three pressure probe wells on the dump; installation of temperature probes, gas monitoring tubes, ground water level probes and pressure probes; acid-base accounting on the drill cuttings; retrieval of the dump building history; acquisition of three sets of monitoring readings; and calculation of physical parameters of the dump. Four drill cutting samples exhibiting more extreme acidic or basic properties have been submitted to Coastech Research Inc. for kinetic test using Humidity Cell technique. Results of these humidity cell tests are incomplete as yet. Data collected have been processed and analyzed. Some preliminary conclusions have been drawn.

TABLE OF CONTENTS

Page

EXECUTIVE SUMMARY i

NOTES ON USE OF UNITS iii

1.0 INTRODUCTION 1

2.0 NORTH WEST DUMP PHYSICAL PROPERTIES 3
  2.1 TOPOGRAPHY 3
  2.2 ORIGINAL SURFACE WATER COURSES 4
  2.3 DUMP BUILDING HISTORY 5
  2.4 DUMP AREA,VOLUME,BULK DENSITY AND AVERAGE POROSITY . 7
  2.5 EARTH WORK REQUIRED IN DUMP RESLOPING 8

3.0 DRILLING PROGRAM 9
  3.1 DRILLING OPERATION AND HOLE INSTALLATION 9
  3.2 DRILLING SAMPLE ANALYSIS 13
  3.3 PROBLEMS IN MONITORING HOLE INSTALLATION 13

4.0 MONITORING RESULTS AND DISCUSSION 16
  4.1 MONITORING INSTRUMENTS AND THEIR PERFORMANCES 16
  4.2 MONITORING RESULTS 19
  4.3 DISCUSSION 19

5.0 KINETIC TEST 32

6.0 CLOSING REMARKS 34

REFERENCES 35

NOTES ON USE OF UNITS

In this report, we have adopted both Metric Units and English Units, since the original information was presented in both. The purpose in doing so is to avoid peculiar numbers caused by conversion. Figures are often given in both systems. When calculations involve both systems, English units are converted into Metric units.

Please note in particular the difference between ton(s) (short ton(s), English, which equals 2,000 pounds) and tonne(s) (Metric, which equals 1,000 kilograms).

Island Copper Mine has used English Units in mapping its property. All the coordinates on maps in this report are in feet (with the word feet omitted) and belong to one coordinate system.

1.0 INTRODUCTION

Island Copper Mine, owned and operated by BHP-UTAH Mines Ltd., is one of Canada's largest open pit, low-grade copper mining operations. It is located on the north shore of Rupert Inlet, about 16 kilometres south of Port Hardy at the north end of Vancouver Island (Figure 1). The revenue producing metals are copper, molybdenum, gold, silver and rhenium.

The operation at Island Copper Mine consists of open pit mining by truck and shovel method in conjunction with the use of an in-pit crushing/conveying system, and milling in its concentrator by a conventional grinding/flotation circuit.

Island Copper Mine has accumulated several land waste dumps through its operation. The North West Dump (NWD), located to the north west of the pit (and hence the name, Figure 2), is a small, isolated land dump consisting primarily of waste rocks from the west and the north west pit walls (also see Figure 2 for divisions of the pit wall). At present, the two seeps originating from this dump (one major and one small) have shown evidences of acid production in the dump.

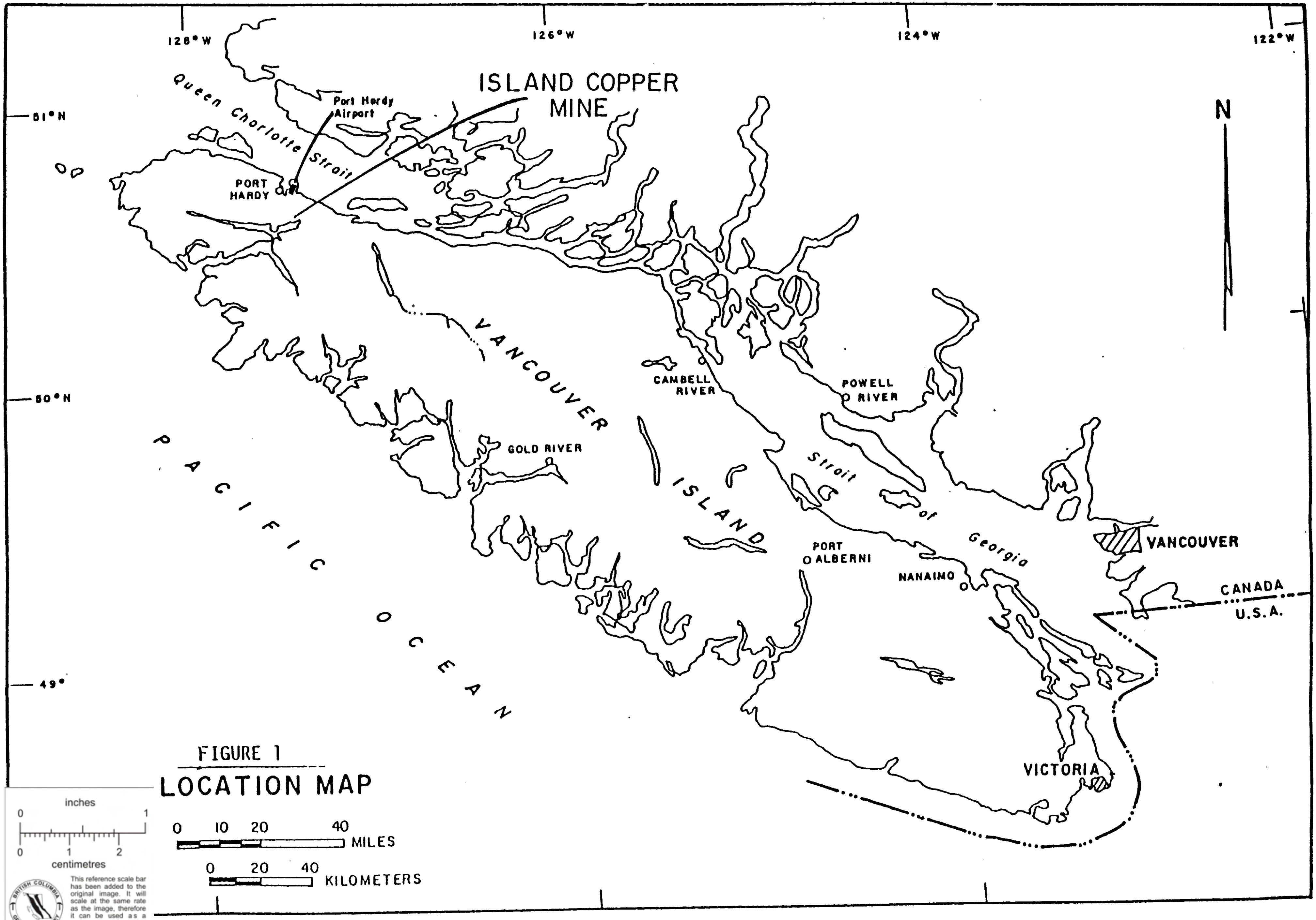


FIGURE 1

LOCATION MAP

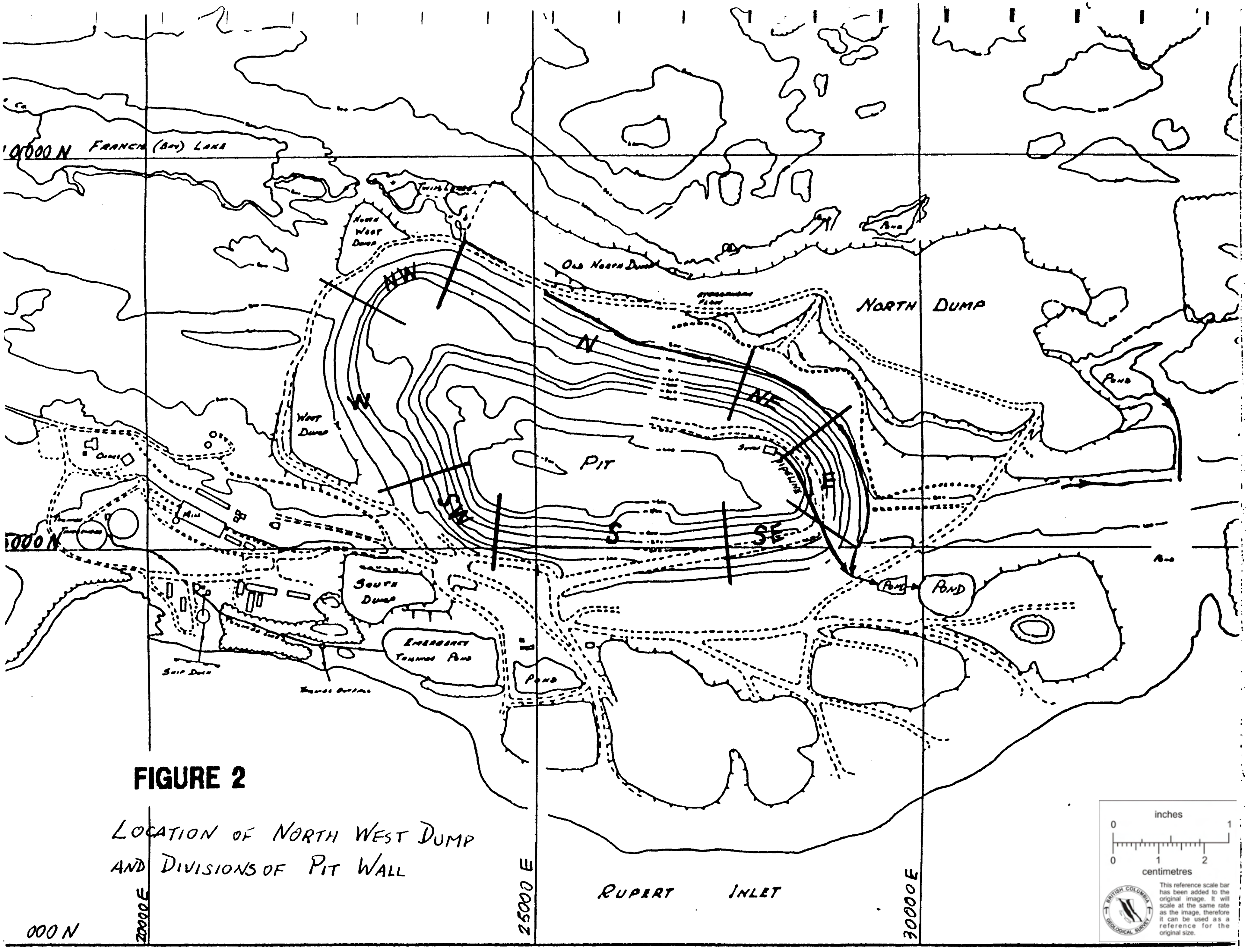


FIGURE 2

LOCATION OF NORTH WEST DUMP AND DIVISIONS OF PIT WALL

This reference scale bar has been added to the original image. It will scale at the same rate as the image, therefore it can be used as a reference for the original size.

Following an acid production study on Island Copper Mine's North Dump in 1988 - 1989 co-initiated by BHP-Utah Mines Ltd. and the University of British Columbia, both Island Copper Mine and UBC considered that it would be more rewarding to move the research focus on to the North West Dump, basically because of its isolation, its relative homogeneity in material and its small size. In May, 1989, a study proposal was made by Ron Hillis of Island Copper Mine to the provincial government proposing the North West Dump project being funded jointly by Island Copper Mine and the Canada-British Columbia Mineral Development Agreement. Subsequently Island Copper subcontracted part of the project to UBC.

This report describes the progress of the project to date, provides an analysis on the data collected, and outlines future research plans.

2.0 NORTH WEST DUMP PHYSICAL PROPERTIES

2.1 TOPOGRAPHY

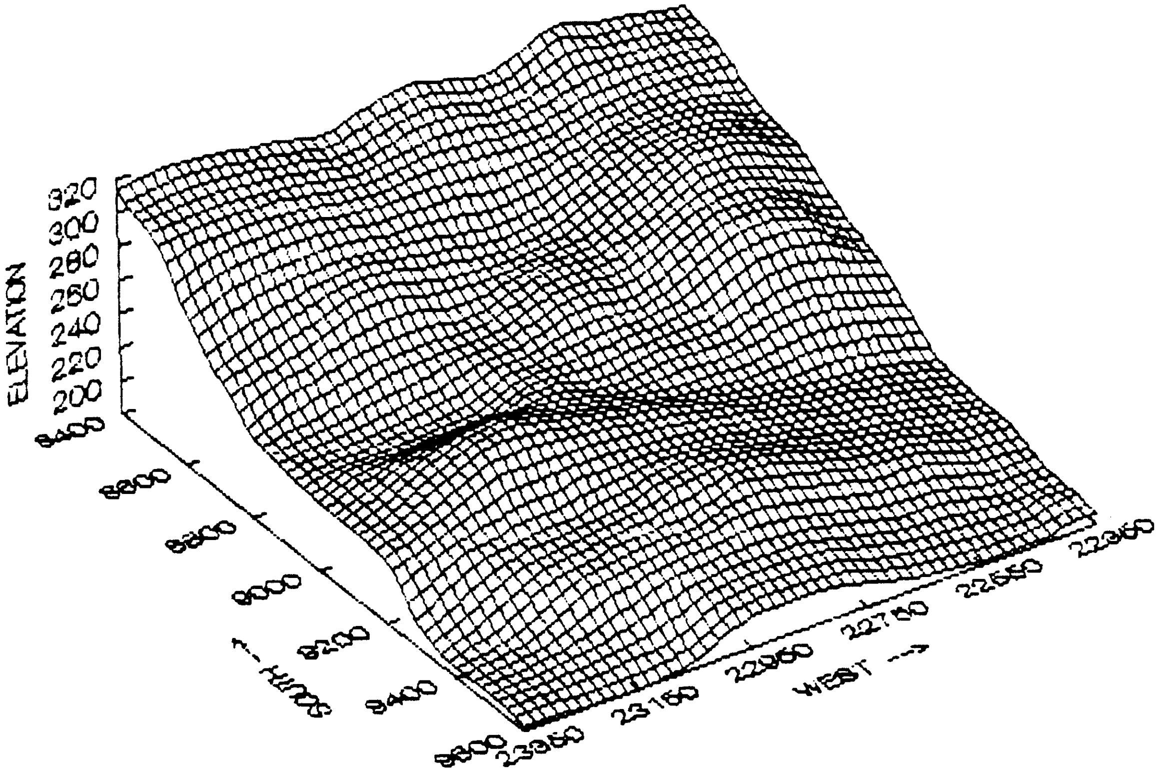
Figure 3 is a screen drawing showing the original topography of the North West Dump area. The pit is located to the south east of this area, i.e., to the left and behind the screen drawing. The area is within the Stephens Creek water shed, is relatively flat and has a low slope dipping slightly towards the north west.

Figures 4 and 5 show two different views of the present topography after the North West Dump has been built.

The first digit (the number 1) of the elevation scale in Figures 3, 4 and 5 was omitted. So 200 (feet) on the scale represents 1200 (feet) in reality.

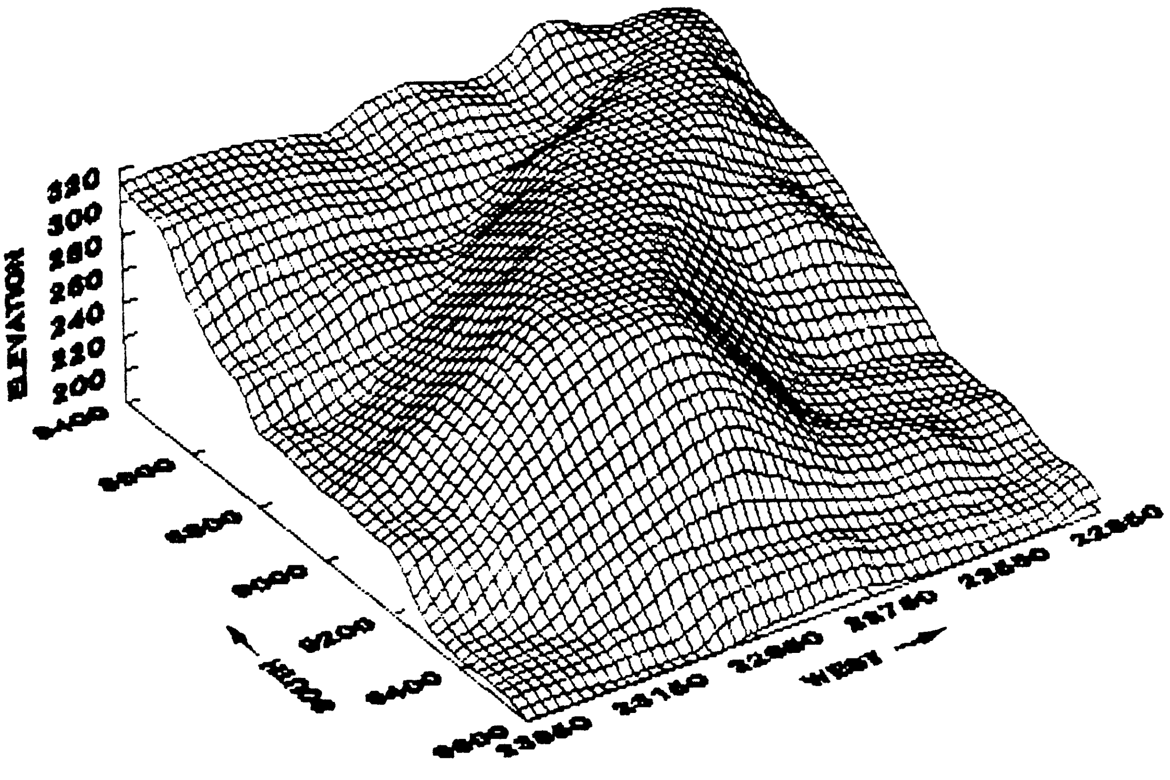
These figures were constructed using two contour maps obtained from Island Copper Mine. The North West Dump area, 8400 feet - 9550 feet north and 22350 feet - 23350 feet east by the Island Copper Mine coordinates, was divided into 1840 square cells on the maps and each square was then assigned an elevation according to the contours. This

FIGURE 3



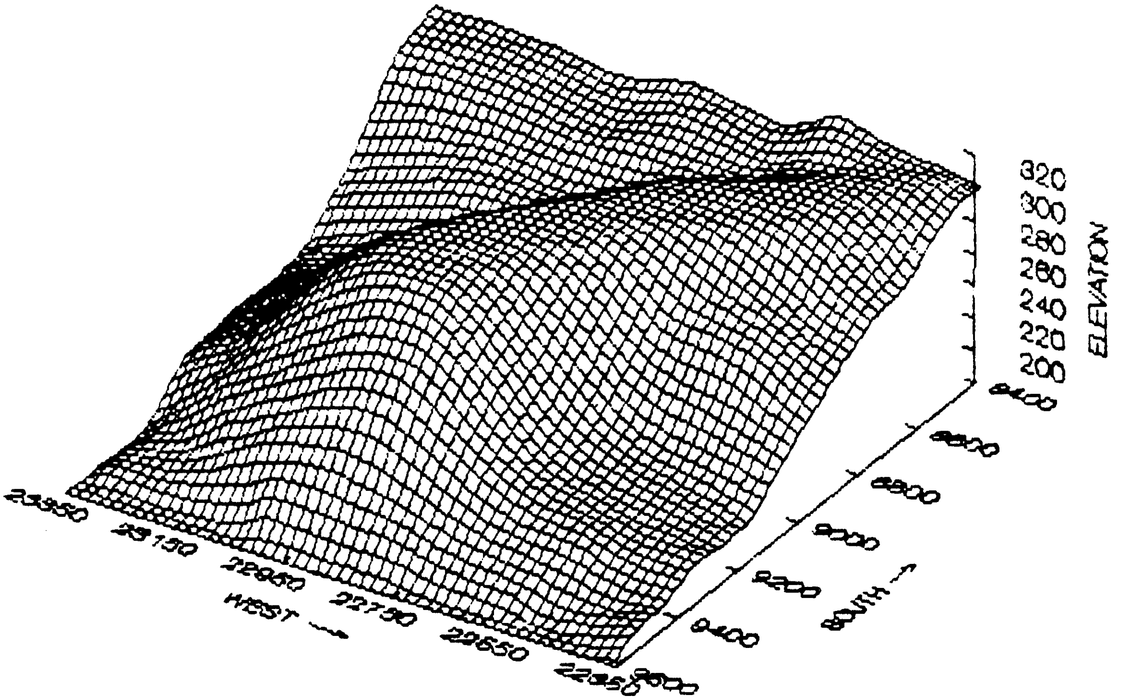
NWD ORIGINAL TOPOGRAPHY

FIGURE 4



NWD PRESENT TOPOGRAPHY

FIGURE 5



NWD PRESENT TOPOGRAPHY

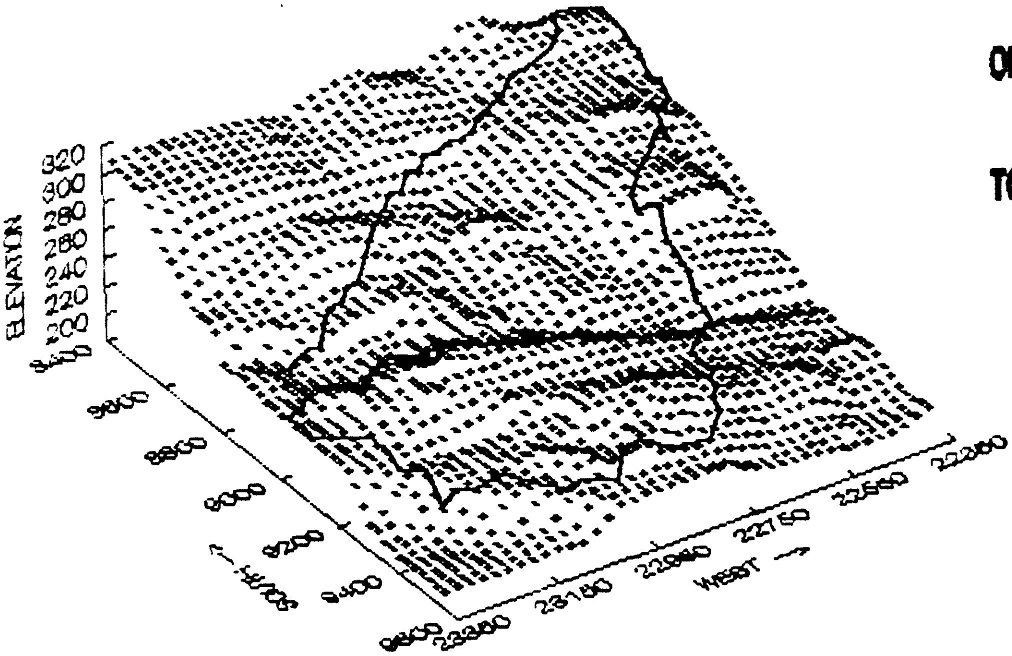
information was also used in the calculation of volume of the North West Dump.

Figure 6 depicts the deposition of the North West Dump on the original topography. The outline of the North West Dump is defined by the points where the present topography meets the original topography.

2.2 ORIGINAL SURFACE WATER COURSES

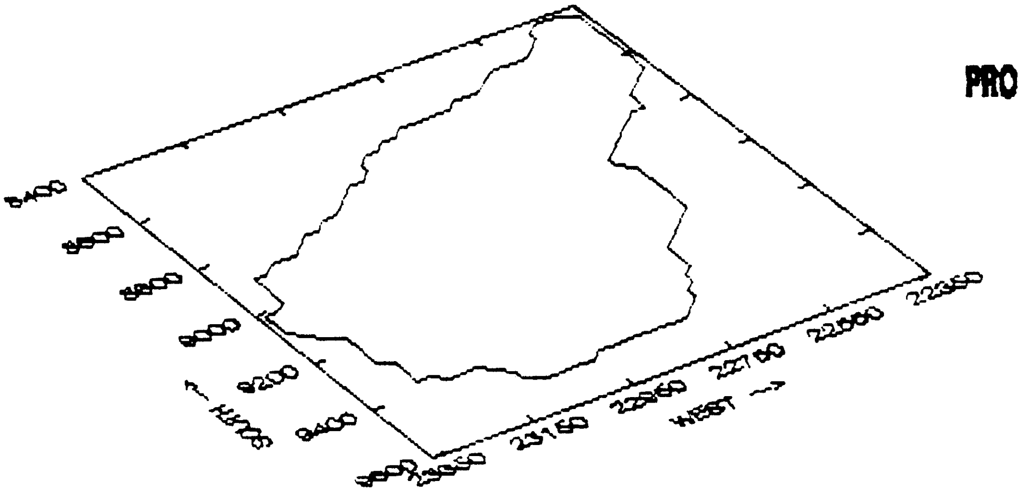
The surface water courses existing before mining activities have been determined according to the original topography. After the dump deposition, the sub-dump water courses remained unchanged due to the high porosity of the dump. These under-dump flows occur during the wet season and emerge at the toe of the dump as seeps. Figure 7 shows the water paths on the original surface and their projection on a horizontal plane. It is evident from Figure 7 that rain water percolating through the North West Dump collect to form two streams. The infiltration of these two streams emerges as seeps at the west toe of the dump. The major one of the two seeps, i.e. the one on the south is regularly sampled for water quality analysis.

DUMP SHAPE



ORIGINAL

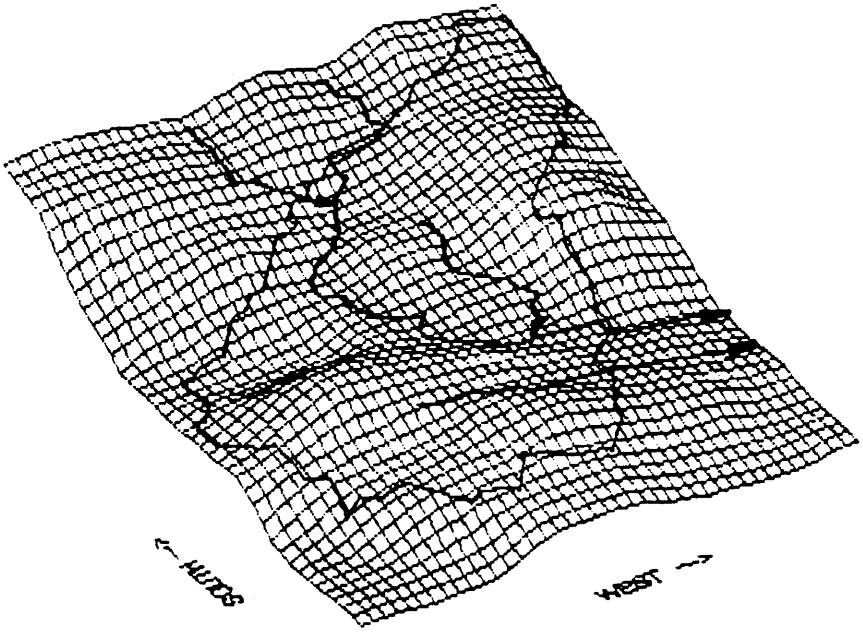
TOPOGRAPHY



DUMP BOUNDARY

PROJECTION ON XY

FIGURE 6 DEPOSITION OF NWD ON ORIGINAL TOPOGRAPHY



ORIGINAL SURFACE

AND WAHER PATH

SURFACE WATERPATH

PROJECTION ON XY

FIGURE 7

SURFACE WATER PATH ON ORIGINAL TOPOGRAPHY

2.3 DUMP BUILDING HISTORY

Deposition of waste material comprising the North West Dump commenced in December, 1982 and ended in January, 1984. However, active dumping on the North West Dump took place only in four months. Of these four batches, the last one was very small and the other three batches accounted for almost the entire dump. Table 1 is a record of the history of building the North West Dump. Note that no glacial till was included in the North West Dump. Figure 8 shows the progress of the dump construction, month by month, during the deposition period. As indicated in Table 1, almost all of the waste material in the North West Dump originated from Benches 1200 feet and 1240 feet of the west or the north west pit wall near the North West Dump (see Figure 2). In Figures 9 and 10, the origins of the three major batches comprising the North West Dump are located in the pit and a map bearing the rock types of the same location in the pit is superimposed so that rock types of each month can be determined. The results are reflected in Table 1.

TABLE 1. ORIGINS OF WASTE MATERIAL IN THE NORTH WEST DUMP

Date of Dumping	Bench	Location in Pit	No. of Loads	Truck Factor+	Tonnage	% of NWD
Jan.,83	1240	NW,W	2433	140.0*	340,620	32.38
Jun.,83	1200	NW	1173	137.6	161,405	15.34
Jul.,83	1200	NW	3895	140.1	545,690	51.87
Jan.84	1160	NW	39	148.0	4,224	0.41
Total			7540		1,051,939	100.00

Rock Type:

Jan.,83 - Andesite in the north west, Pyrophyllite and some Andesite in the west

June,83 - Andesite

July,83 - Andesite

Notes:

+ Truck factors are those found in the monthly summary report as average truck factors. No. of Loads x Truck Factor = Tonnage

* This is an assumed value.

FIGURE 8

ICM NORTH WEST DUMP (NWD)
DUMP BUILDING HISTORY

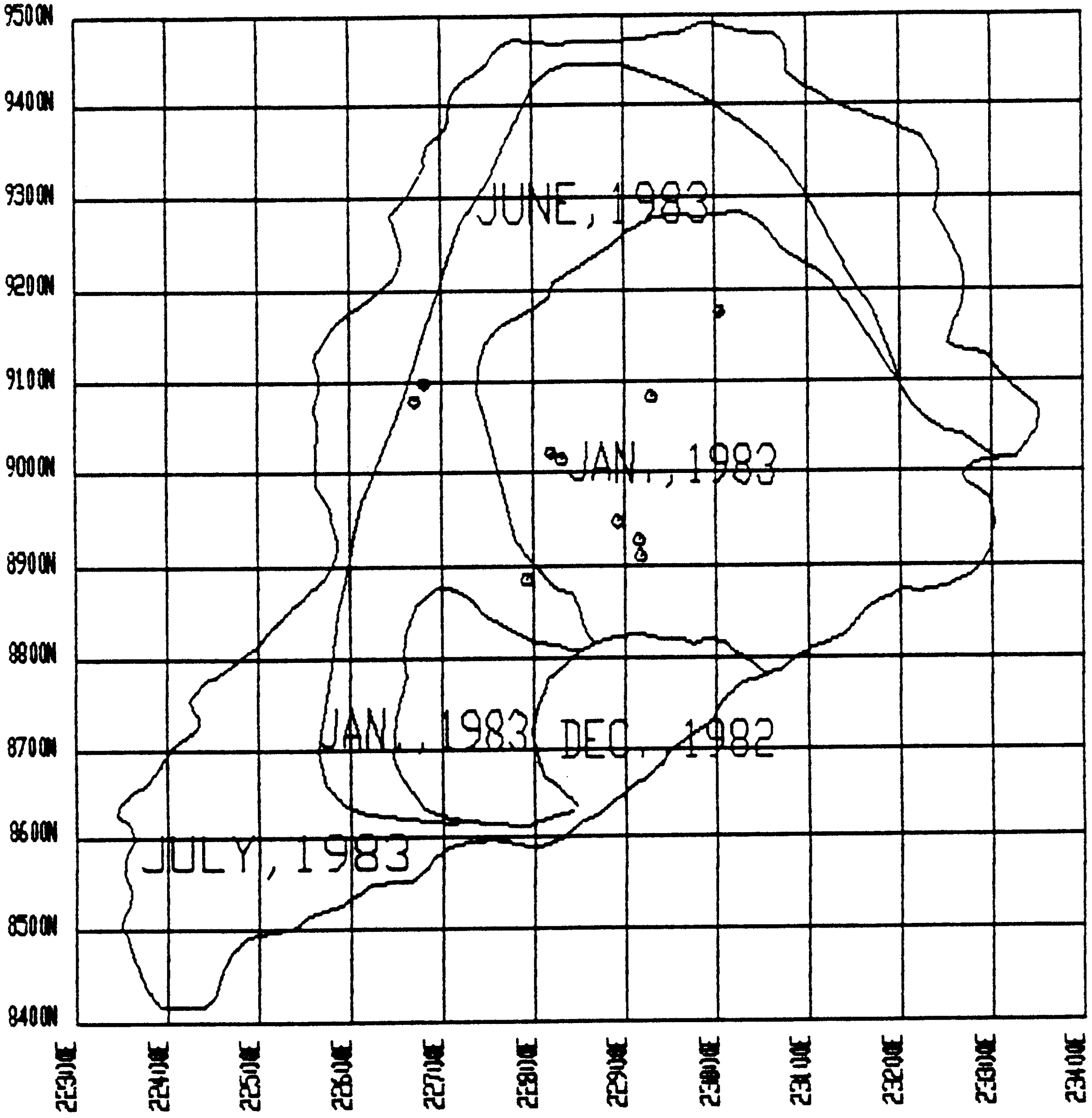


FIGURE 9

ROCK TYPE FOR BENCH 1200

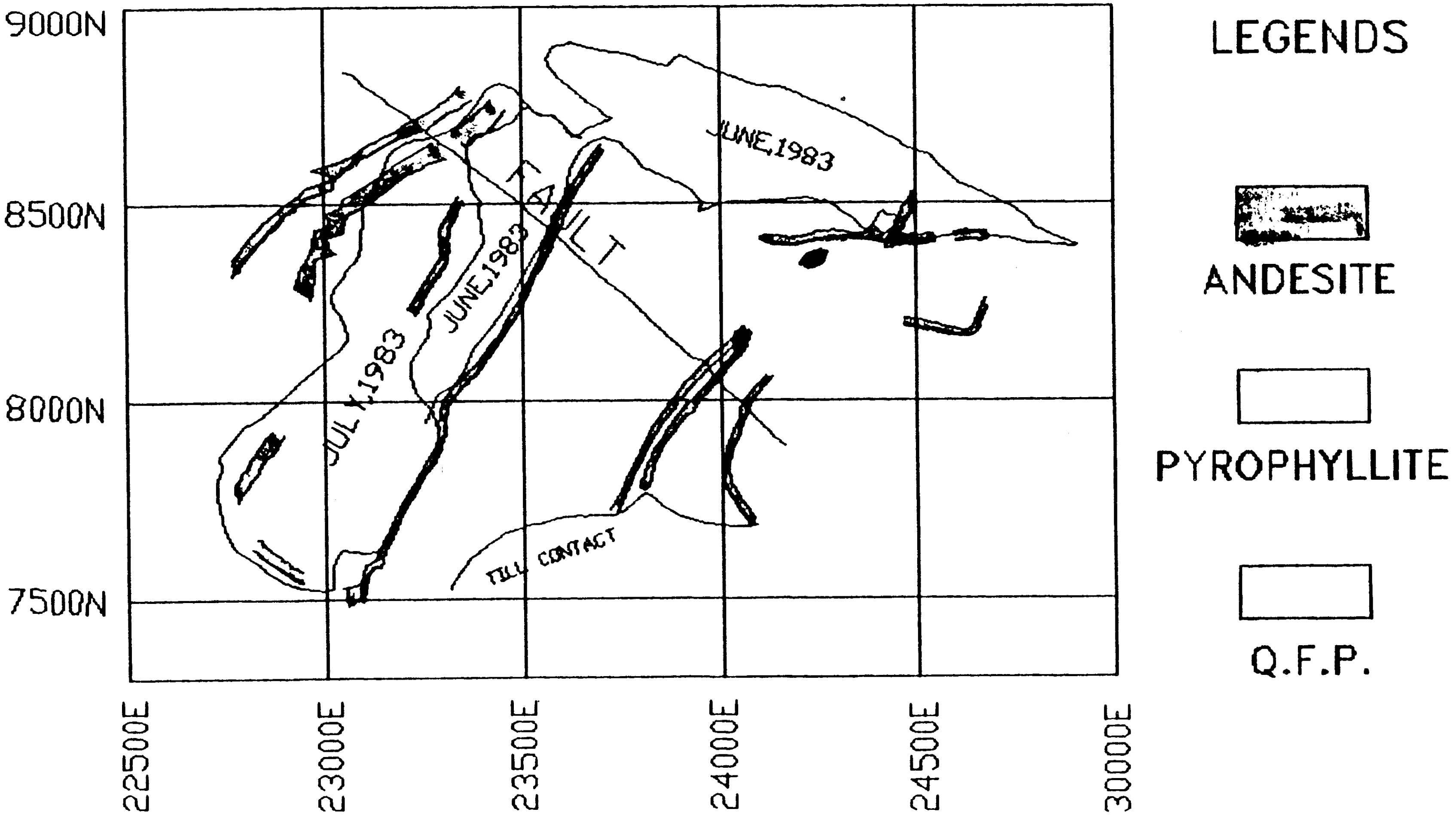
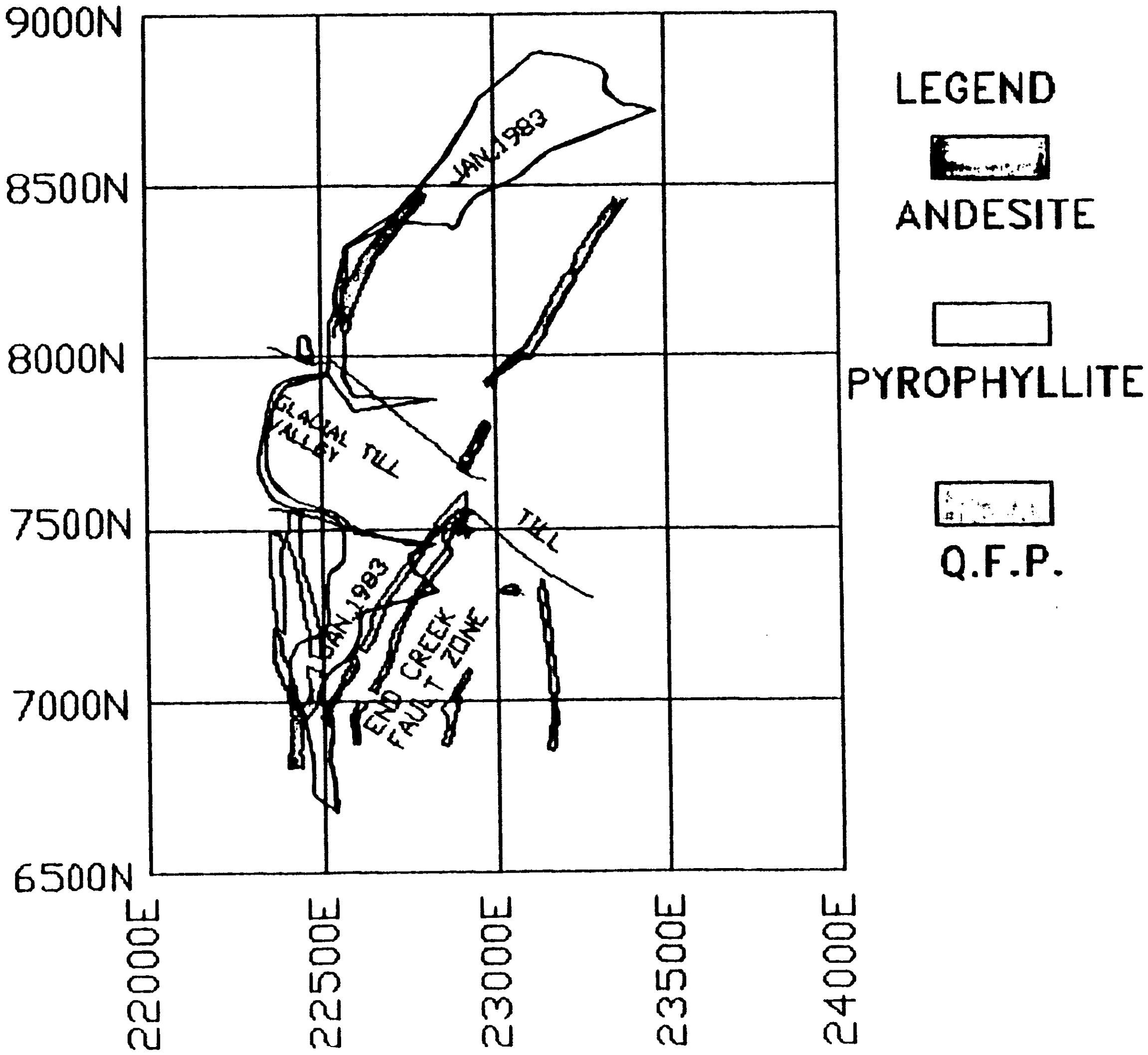


FIGURE 10

ROCK TYPE FOR BENCH 1240



2.4 DUMP AREA, VOLUME, BULK DENSITY AND AVERAGE POROSITY

The area of the horizontal projection of the North West Dump, as defined in the previous section, is 568,720 square feet, or 5.3 hectares. The perimeter of the horizontal projection measures 3473 feet. The top of the dump has an area of 169,037 square feet (1.6 Hectare) and a perimeter of 2260 feet (Figure 11).

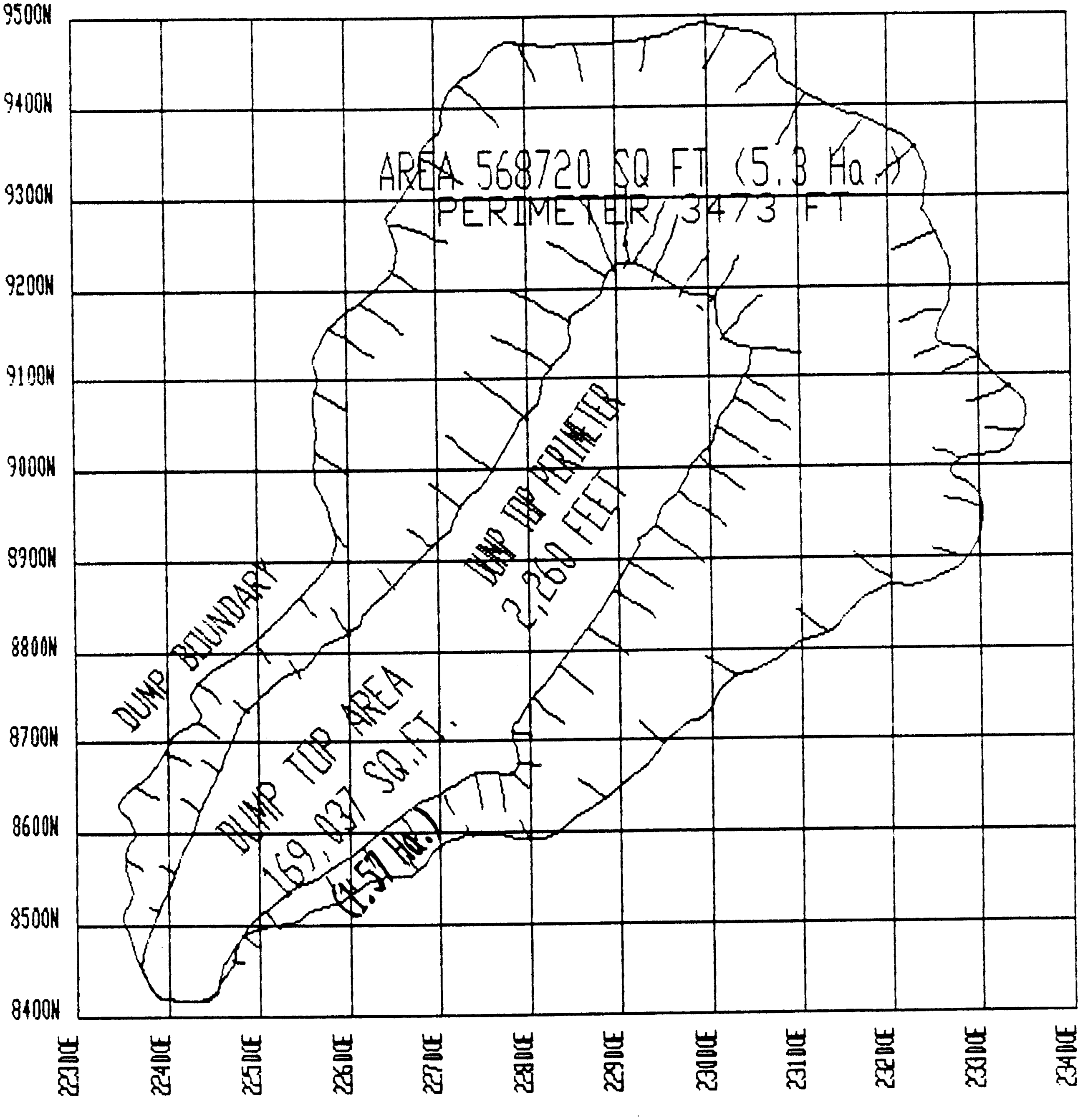
The volume of the North West Dump is calculated to be 18,242,946 cubic feet, or 516,582 cubic metres.

The total mass of the material in the North West Dump as recorded in the monthly mine summary sheets is 1,051,939 tons (English), or 954,319 Tonnes (Metric).

From the total volume and total mass, the bulk density of the dump material is calculated to be as 1847.37 kg/m^3. This is close to, but somewhat less than the bulk density calculated for the North Dump (1965 kg/m^3). This is attributed to the differences in composition: more than 50% of the North Dump is glacial till, which results in a lower average porosity (20.35%) by filling the voids between the rocks, while the North West Dump is composed of 100% waste rock.

FIGURE 11

ICM NORTH WEST DUMP (NWD)



Assuming a solid specific gravity of 2650 kg/m^3 for the solid waste dump material, a porosity of 30.29% is obtained.

2.5 EARTH WORK REQUIRED IN DUMP RESLOPING

Two orthoganal sections A-A and B-B were constructed through the North West Dump as shown in Figure 12. Figures 13 through 15 present section A-A and Figure 16 to Figure 17 section B-B. Notice that all these illustrations are drawn to the scale. A slope of 1:3 is drawn on each figure to compare with the currently existing slope. It can be seen that all three slopes are very close to 1:3. The north west slope and the north east slope are slightly steeper than 1:3 while the south east slope is slightly less than 1:3. The slope of 1:3 is the maximum slope recommended to accommodate packer machines necessary for later installation of a low permeability soil cover. Therefore, if a resloping is to be carried out, the earth work involved is minimal. A rough calculation shows that this earth work will amount to moving only 38,500 tons, or 3.7% of the entire dump.

FIGURE 12

ICM NORTH WEST DUMP (NWD)

SECTIONS A-A AND B-B OF NWD

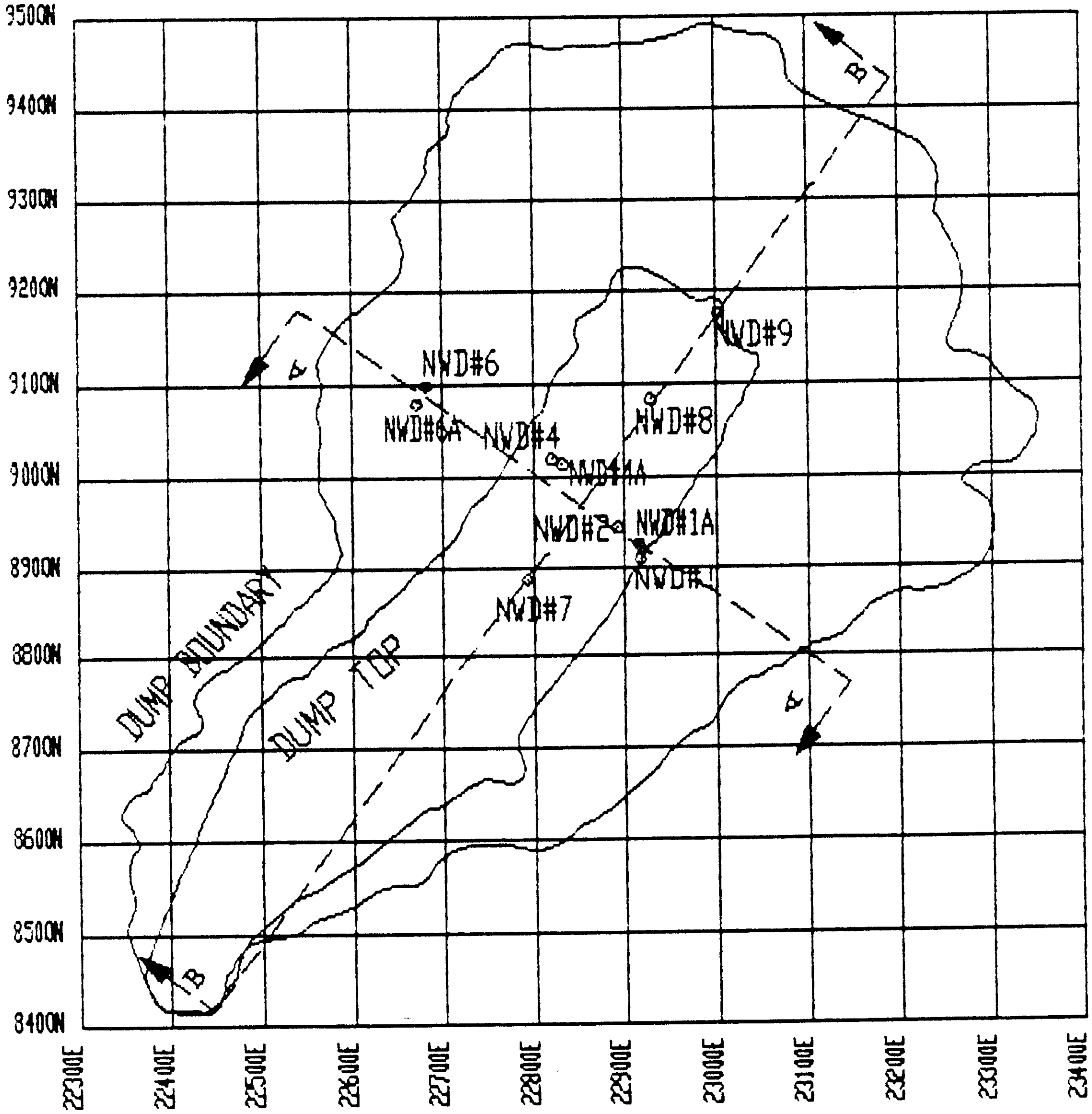


FIGURE 13

SECTION A-A OF NORTH WEST DUMP

EARTHWORK REQUIRED IN RESLOPING

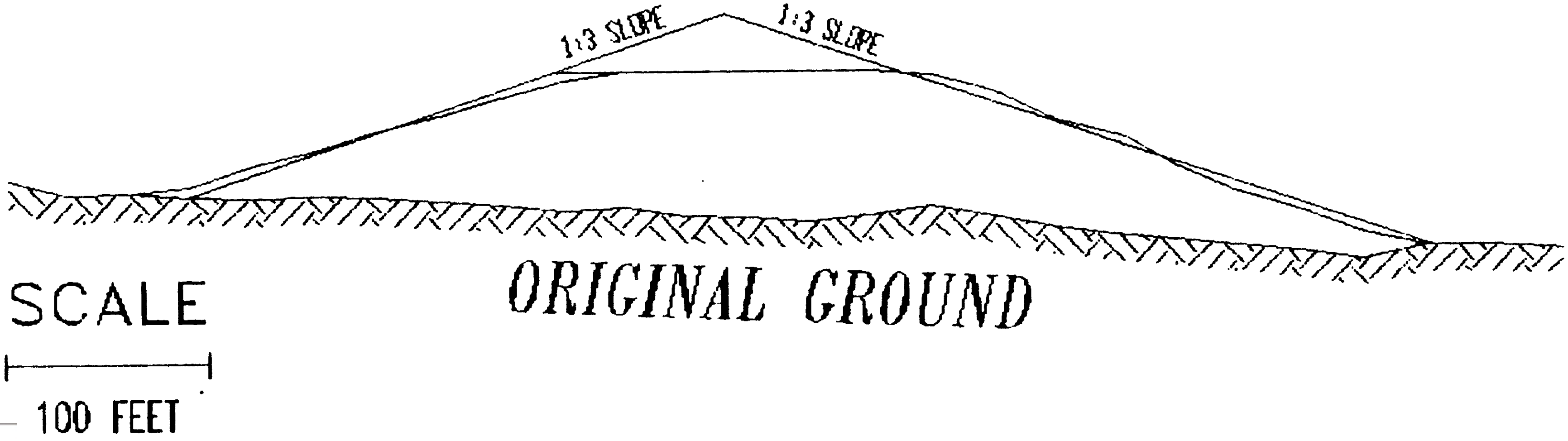
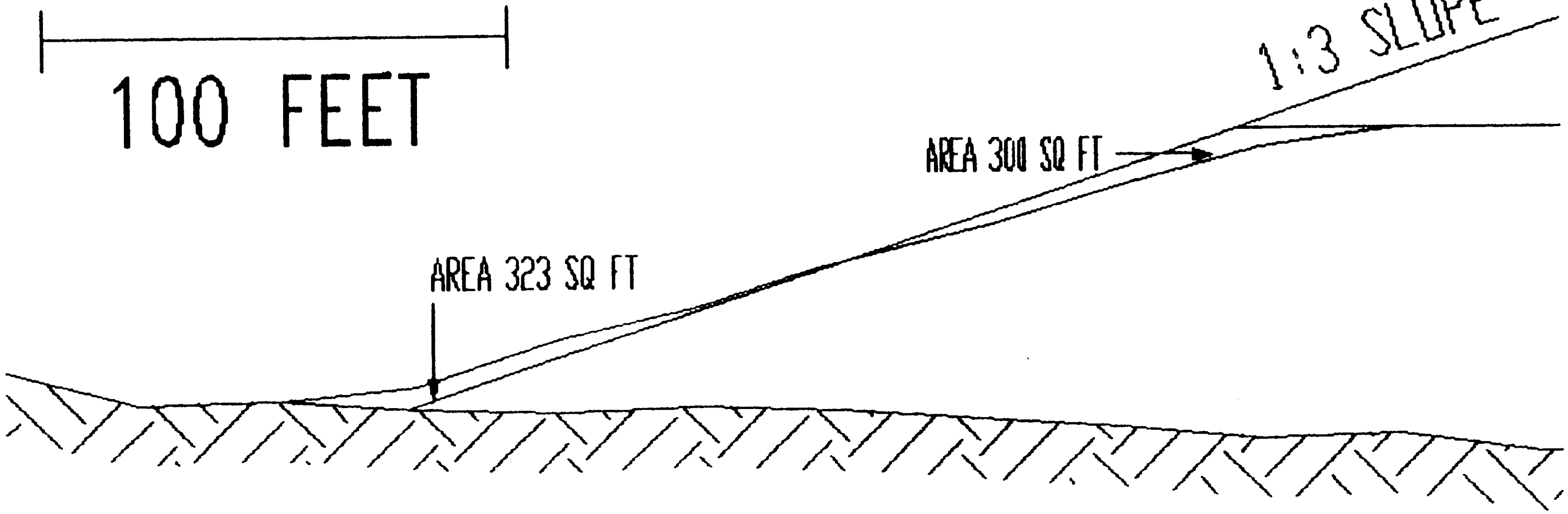


FIGURE 14

EXPANDED VIEW OF SECTION A-A'S LEFT SLOPE



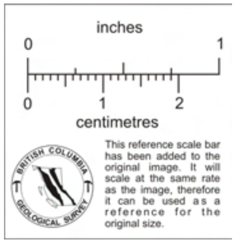


FIGURE 15

EXPANDED VIEW OF SECTION A-A'S RIGHT SLOPE

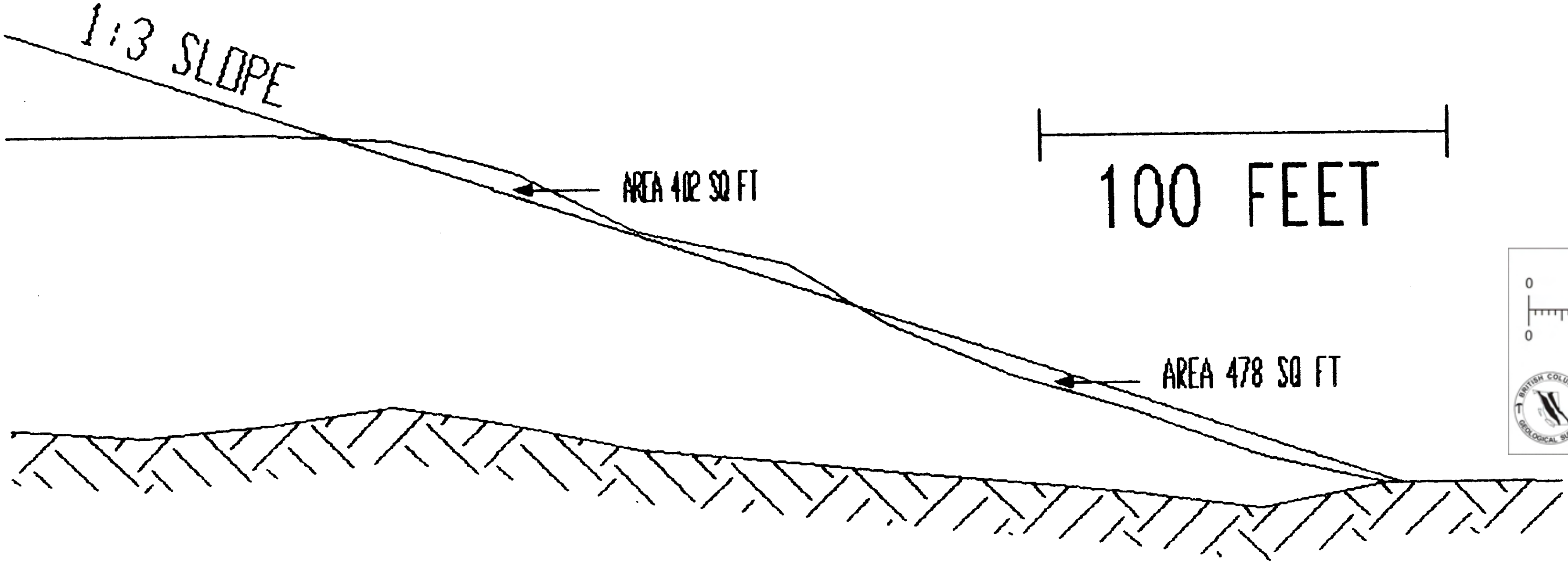


FIGURE 16

SECTION B-B OF NORTH WEST DUMP

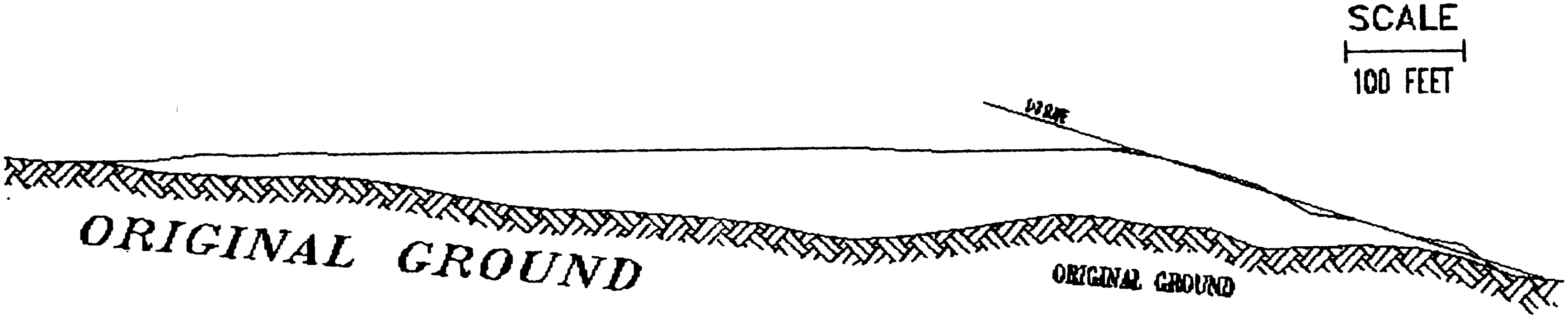
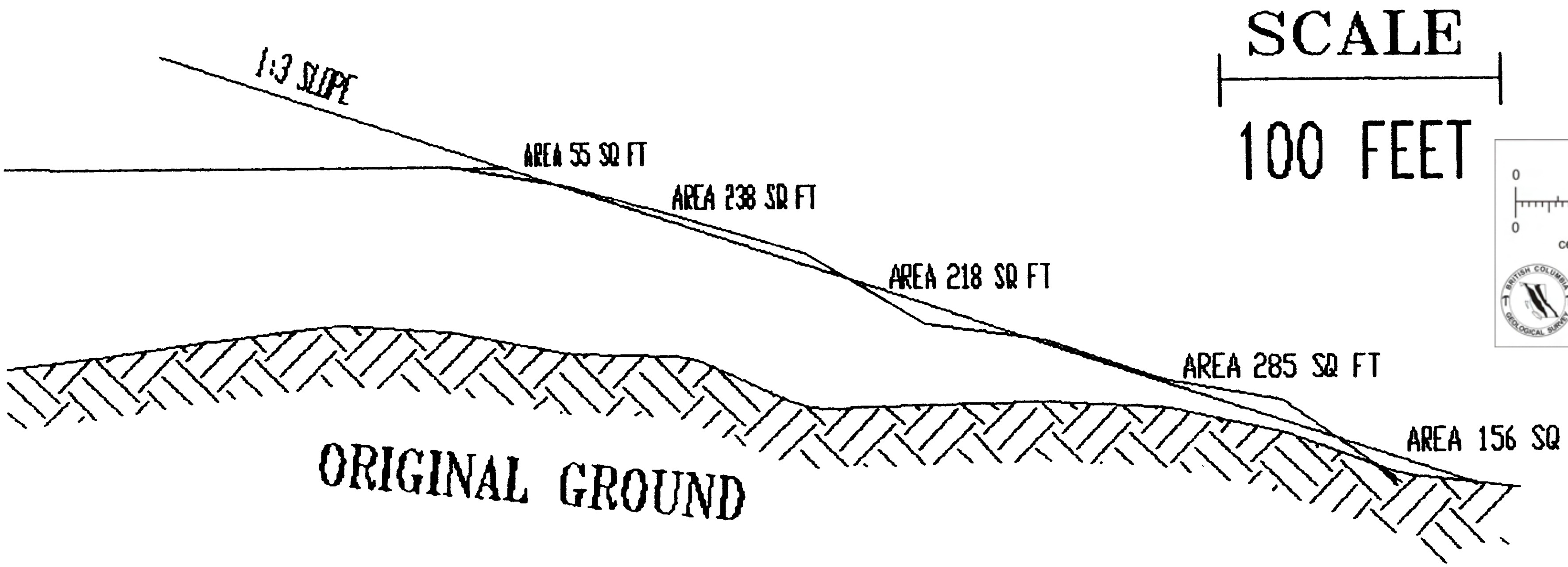


FIGURE 17

EXPANDED VIEW OF SECTION B-B'S SLOPE



3.0 DRILLING PROGRAM

3.1 DRILLING OPERATION AND HOLE INSTALLATION

The North West Dump drilling program was devised to achieve the following:

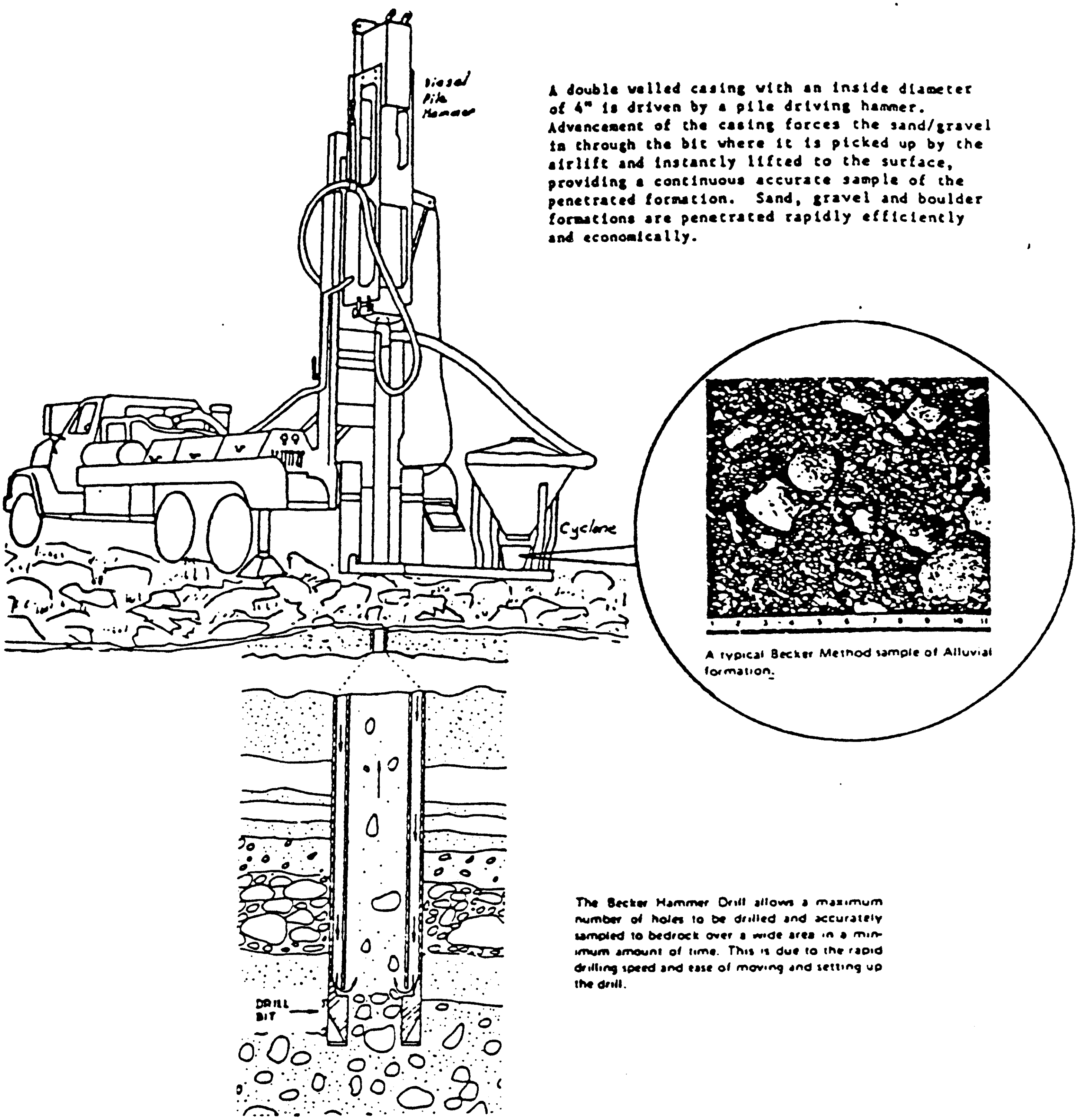
- To sample the dump
- To install gas content-temperature monitoring probes
- To place piezometers down to the bottom of the dump to measure the water table
- To install PVC pipes for housing gas pressure sensors

Drill holes were located along two straight lines intersecting at an angle of 73.8 degrees. Originally 10 drill hole locations were planned but only seven of them were actually drilled due to the budget limit.

Drilling operation was performed by a contractor, Foundex, in September, 1989 using the Becker Drilling method. Shown in Figure 18 is a Becker drill used in the drilling. Becker drilling is a proven method for waste dump drilling for its fast penetration speed, good cutting returns and reasonable cost.

FIGURE 18 THE BECKER METHOD

A double welled casing with an inside diameter of 4" is driven by a pile driving hammer. Advancement of the casing forces the sand/gravel in through the bit where it is picked up by the airlift and instantly lifted to the surface, providing a continuous accurate sample of the penetrated formation. Sand, gravel and boulder formations are penetrated rapidly efficiently and economically.



A typical Becker Method sample of Alluvial formation.

The Becker Hammer Drill allows a maximum number of holes to be drilled and accurately sampled to bedrock over a wide area in a minimum amount of time. This is due to the rapid drilling speed and ease of moving and setting up the drill.

The following observations were made during the drilling operation:

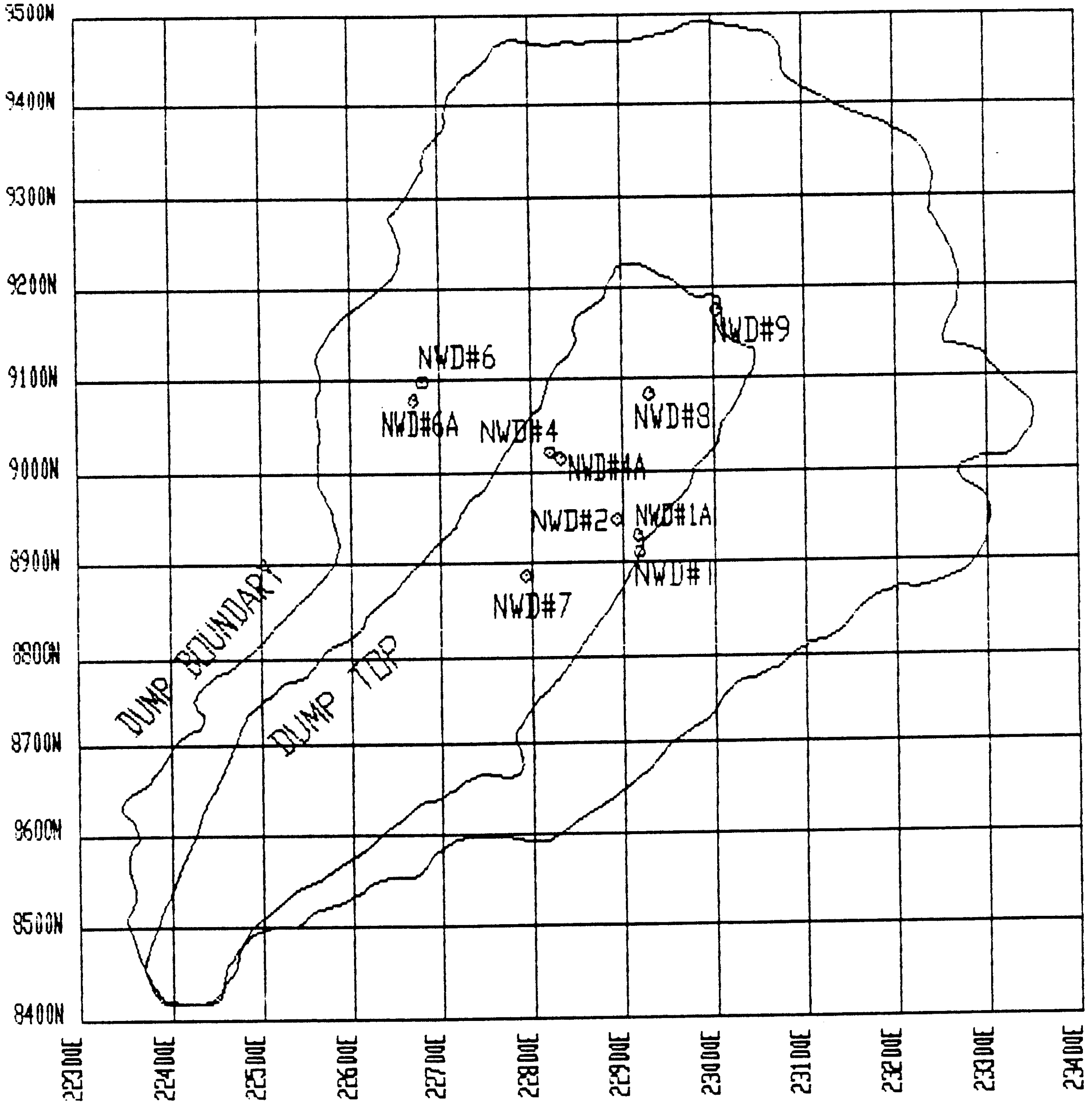
- A large proportion of the compressed air was lost in the dump;
- Large boulders were frequently encountered (diameters up to 2 - 3 feet), in some instances boulders were visible near the surface when the drill casing was pulled out;
- Penetration to the original ground surface was usually signalled by one or more of the following: appearance of wood debris in cuttings, soil samples, sudden slow down of penetration speed, and very dry, grey fine cuttings accompanied by bouncing of the drilling steel;
- No water table was met except at the bottom of hole NWD #6 (40 feet), where a foul, muddy water containing wood debris was blown up;
- The drill casing was deflected away from vertical orientation several times. This was a indication of the looseness and coarseness of the dump: when the drill bit encountered a big boulder at some oblique angle, it would break the boulder if there was enough support from the dump to hold the drilling case vertical, namely if the dump is compact enough; but if the dump was too loose the drill bit tended to slip off the boulder.

Figure 19 shows the locations of the finished 7 drill holes on the North West Dump as surveyed by Island Copper Mine engineering personnel. Some of them are a little off the straight line planned. During the drilling

FIGURE 19

ICM NORTH WEST DUMP (NWD)

DRILLHOLE LOCATIONS



some holes had to be redrilled one to three times because the drill steel was deflected by large boulders from a vertical position.

There are three twin holes in Figure 19, namely holes #1, #4 and #6. The major holes were named NWD #1, NWD #4 and NWD #6 and their corresponding sister holes were named NWD #1A, NWD #4A and NWD #6A. The latter three came into being because there was great difficulty backfilling the holes if the pressure probe pipes planned for these three locations were placed in the same holes which each had already accommodated a temperature probe pipe and a piezometer pipe. A decision was made instead to drill a separate hole close by for each location to house the pressure probe pipe.

Holes NWD #2, NWD #4 and NWD #6 were located to intersect major original water course. Figure 20 shows the location of the finished holes in relation to the original water courses determined from Figure 7.

Figures 21 and 22 are A-A and B-B section views of the dump with the drill holes shown. Notice that the drawings are to scale, which is the same for both horizontal and vertical direction.

Each drill hole was installed immediately after the drilling was terminated at the original ground surface with the drill steel casing still in place. A typical installation is described in detail in Figure 23. The installation procedure began with sealing off the bottom with bentonite pellets wetted with water. Then a one-inch-inside-diameter

FIGURE 20

ICM NORTH WEST DUMP (NWD)

ORIGINAL WATER PATH UNDER DUMP

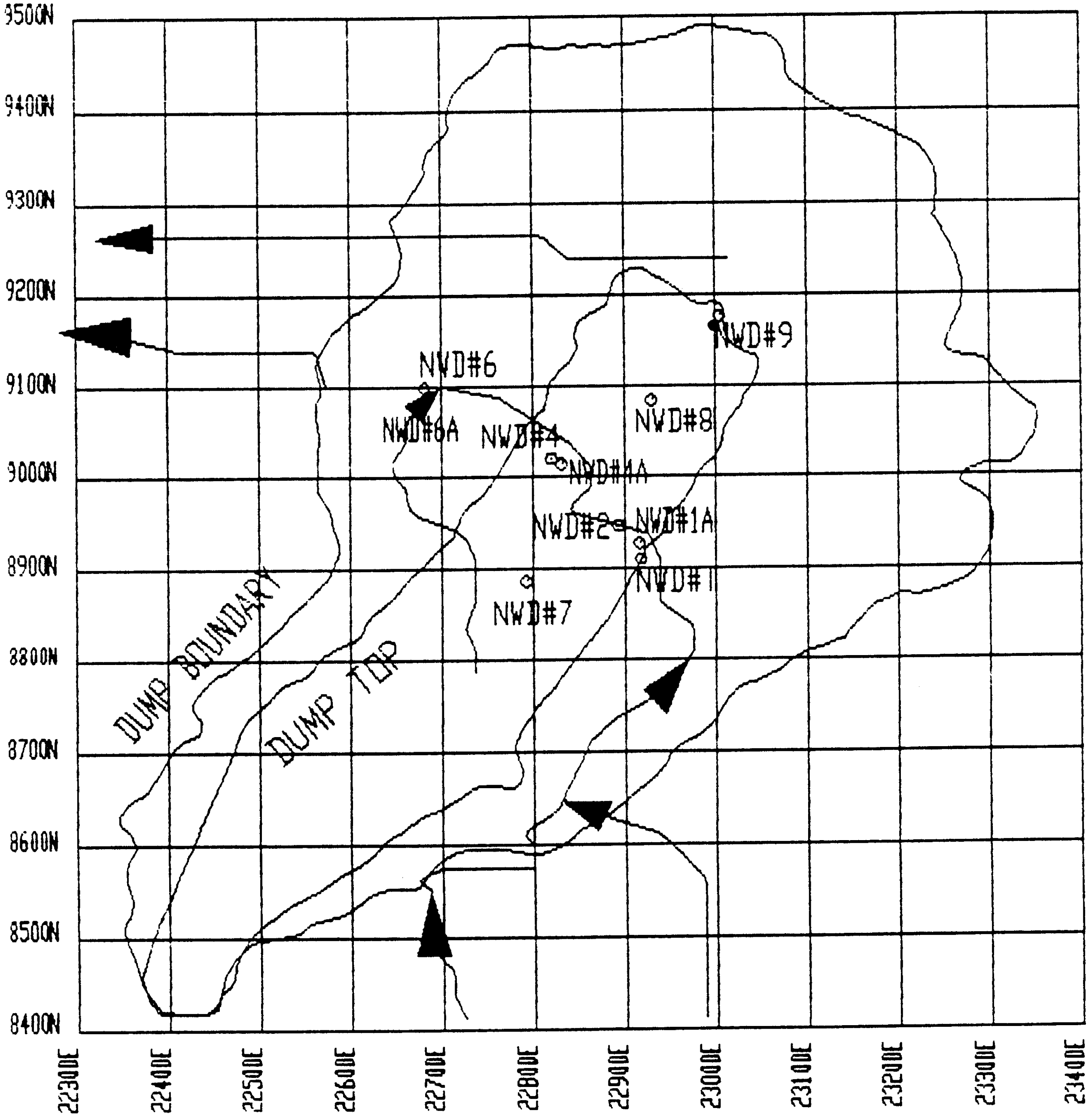
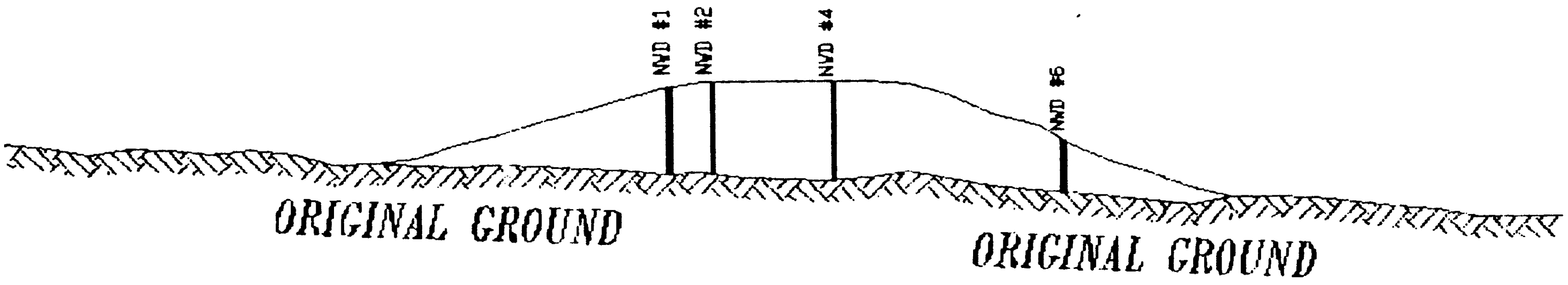


FIGURE 21

SECTION A-A OF NORTH WEST DUMP



SCALE

100 FEET

FIGURE 22

SECTION B-B OF NORTH WEST DUMP

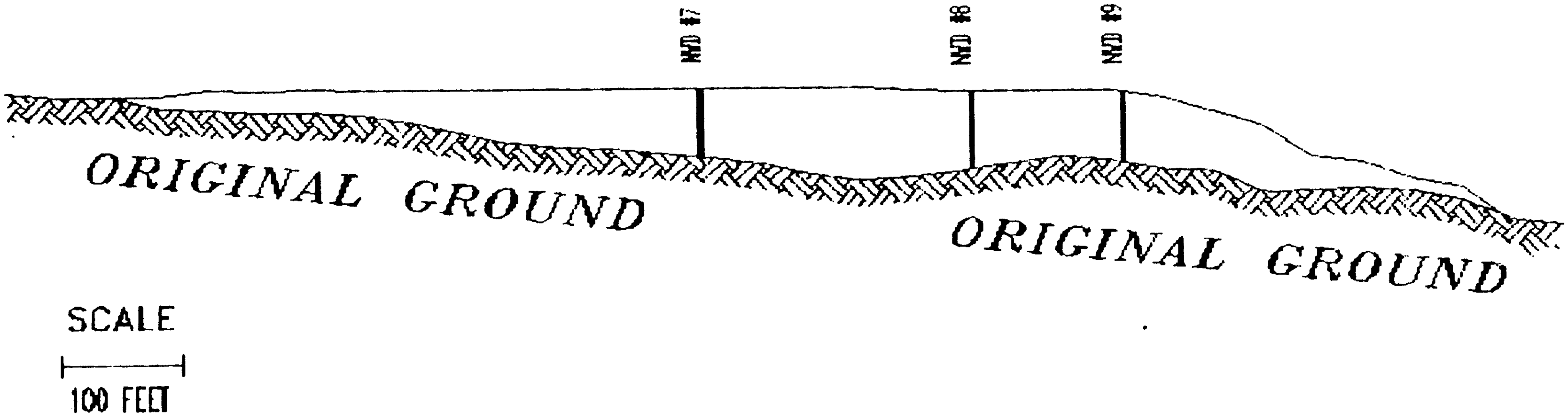
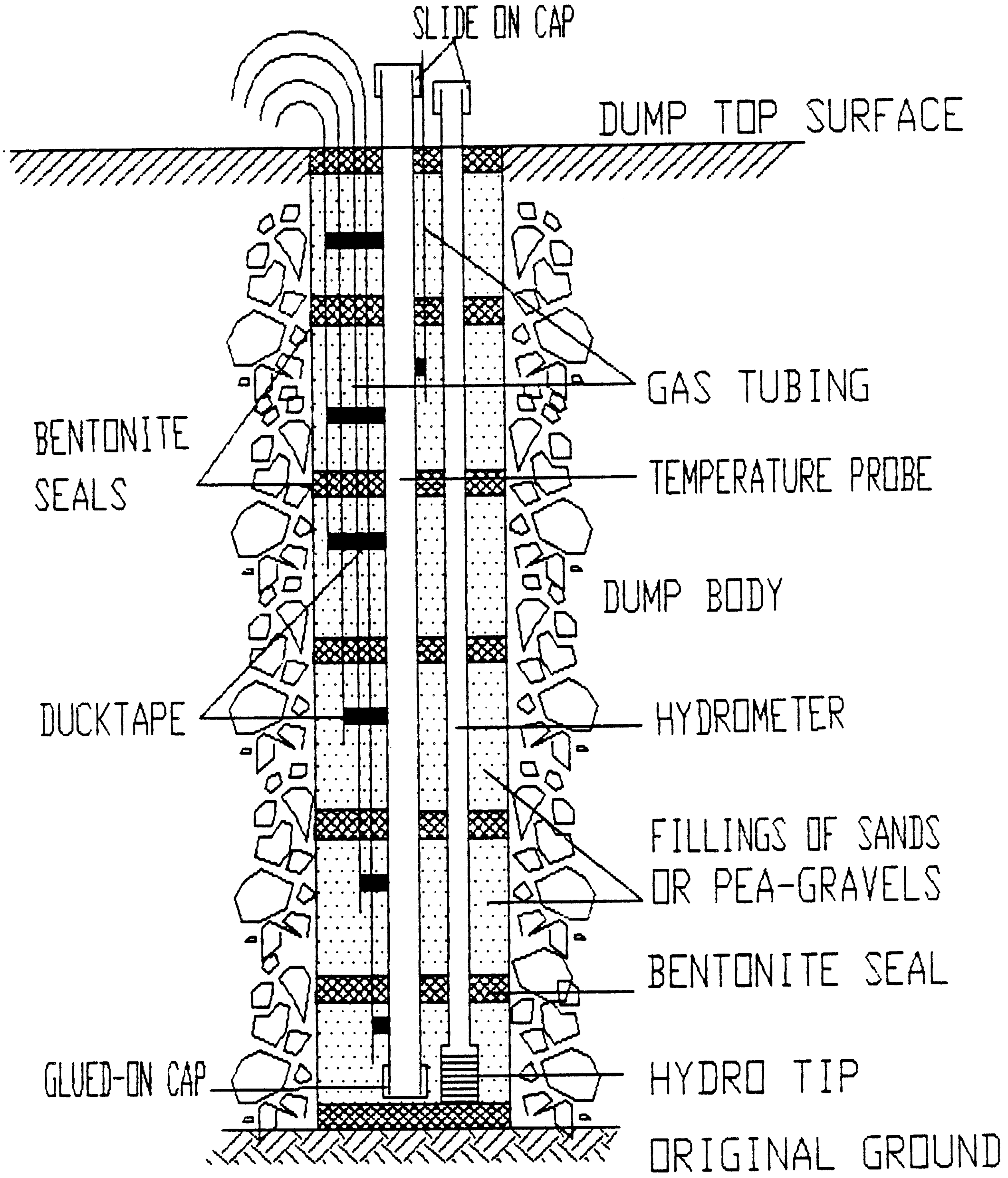


FIGURE 23 HOLE INSTALLATION



PVC pipe (used to accommodate temperature probes), sealed at bottom using a glued-on cap was lowered to the bottom. Along the outside of the temperature probe were attached 3/16 inch plastic tubes by means of duck tape. The first plastic tube was terminated at 6 inches above the bottom bentonite seal and from there up more tubes were attached each to terminate at two meter intervals. The last plastic tube terminated between two and four meters below the dump surface. The plastic tubes were for the purpose of sampling gases in the dump at various strata. In some of the holes, a second PVC pipe of 3/4 inch diameter with a hydro tip mounted at the end was placed in order to monitor the water table variation within the dump. All the PVC pipes were left to stick up about two feet above the dump surface to allow possible future resurfacing of the dump.

The gaps between the outside wall of the PVC pipe(s) and the inside wall of the drill hole w~~as~~ere backfilled with silica sand and/or pea gravels as the drill steel casing was progressively pulled out. A bentonite seal was applied in the middle between the openings of every two gas sampling tubes. The purpose of this seal was to avoid vertical gas flow during gas sampling.

3.2 DRILLING SAMPLE ANALYSIS

Cuttings were collected during the drilling operation at eight foot intervals. An acid-base accounting was conducted by Island Copper Mine Environmental Lab on these samples. The results are presented in Table 2. Acid Production Potential (APP) was calculated directly from the total sulfur content. Acid Consuming Potential (APP) was obtained by the cold acid titration method as outlined by Sobek et. al. The acid-base accounting results are plotted and correlated with the monitoring results in Section 4.

3.3 PROBLEMS IN MONITORING HOLE INSTALLATION

Costs of installing the monitoring holes turned out to be twice as high as originally predicted. Three of the ten wells originally planned had to be cancelled. Reasons responsible for the exceptionally high cost will become clear from the following discussion of the problems encountered in the drilling program.

The drilling operation went quite smooth as expected except that at some locations the drill bit was deflected by large boulders from vertical positions and these holes had to be restarted. In a few cases the hole had to be restarted after 40 feet had been driven. The Becker drill was designed to drill vertically; too much deflection from the vertical position would make the Becker drill unable to operate.

TABLE 2 NORTH WEST DUMP ACID-BASE ACCOUNTING

NWD #1

Interval (ft.)	APP (kg H2SO4/Tonne)	ACP (kg CaCO3/Tonne)	NNP (kg CaCO3/Tonne)
0-7	45.9	32.4	-13.5
7-15	60.0	58.3	-1.7
15-23	68.3	55.6	-12.7
23-31	59.7	34.4	-25.3
31-39	52.7	44.4	-8.3
39-47	65.8	25.9	-39.9
47-55	56.7	41.1	-15.6
55-63	47.5	19.0	-28.5
63-68	49.6	31.1	-18.5
68-71	39.2	29.8	-9.4

NWD #2

Interval (ft.)	APP (kg H2SO4/Tonne)	ACP (kg CaCO3/Tonne)	NNP (kg CaCO3/Tonne)
0-7	32.5	58.3	25.8
7-15	34.3	47.8	13.5
15-23	30.6	56.5	25.9
23-31	222.3	0.0	-222.3
31-39	91.6	36.0	-55.6
39-47	59.4	31.1	-28.3
47-55	30.9	47.5	16.6
55-63	44.4	23.6	-20.8
63-68	43.5	38.3	-5.2

NWD #4

Interval (ft.)	APP (kg H_2SO_4/Tonne)	ACP (kg $CaCO_3$/Tonne)	NNP (kg $CaCO_3$/Tonne)
0-7	40.4	47.0	6.5
7-15	43.2	78.0	34.8
15-23	26.6	69.7	43.1
23-31	38.6	75.7	37.1
31-39	23.3	70.3	47.0
39-47	20.2	89.6	69.4
47-55	115.8	100.4	-15.4
55-63	74.4	95.5	21.1
63-71	141.2	13.3	-127.9
71-79	134.4	17.9	-116.6

NWD #6

Interval (ft.)	APP (kg H_2SO_4/Tonne)	ACP (kg $CaCO_3$/Tonne)	NNP (kg $CaCO_3$/Tonne)
0-7	47.5	85.1	37.6
7-15	33.1	79.7	46.6
15-23	27.9	76.3	48.3
23-31	9.5	78.9	69.4
31-39	4.1	89.6	85.6
39-47	11.0	51.2	40.2

NWD #7

Interval (ft.)	APP (kg H2SO4/Tonne)	ACP (kg CaCO3/Tonne)	NNP (kg CaCO3/Tonne)
0-7	60.6	45.5	-15.1
7-15	75.8	45.8	-30.0
15-23	15.4	64.5	49.1
23-27	80.5	46.1	-34.5
27-31	15.31	30.91	15.6
31-36	19.9	30.8	10.9
36-39	60.33	23.38	-37.0
39-47	57.3	23.4	-33.9
47-55	67.4	36.4	-31.0
55-57	19.6	37.4	17.8
57-63	5.2	20.0	14.8

NWD #8

Interval (ft.)	APP (kg H2SO4/Tonne)	ACP (kg CaCO3/Tonne)	NNP (kg CaCO3/Tonne)
0-7	39.2	59.4	20.2
7-15	33.4	65.8	32.4
15-23	19.0	61.1	42.1
23-31	43.8	58.3	14.5
31-39	21.4	48.8	27.4
39-47	104.7	45.5	-59.3
47-55	29.3	47.8	18.5
55-63	21.6	12.8	-8.8
63-66	12.7	46.0	33.3
66-70	6.8	47.8	41.0

NWD #9

Interval (ft.)	APP (kg H2SO4/Tonne)	ACP (kg CaCO3/Tonne)	NNP (kg CaCO3/Tonne)
0-7	75.3	55.1	-20.2
7-15	28.8	63.7	34.9
15-23	72.9	58.5	-14.4
23-31	64.6	17.5	-47.1
31-39	40.4	61.1	20.7
39-47	39.8	54.6	14.8
47-55	125.6	42.3	-83.3
55-63	21.1	33.2	12.1
63-66	103.2	24.0	-79.2
66-67	13.4	42.8	29.4

The major cause of over expenditure in the drilling program was the extended hours of hole installation. This in turn was caused by the very time consuming process of backfilling the gap between the monitoring equipment and the inside wall of the hole and sealing between sampling tube openings. Backfilling and sealing was considered necessary to impede the vertical gas flow during gas sampling. Without backfilling and sealing, the dump material that had collapsed around the gas monitoring tubes after the drill casing was withdrawn could have been too loose. In regions of high temperature gradient, vertical gas flows would then have been highly likely.

During backfilling, large quantities of sands and pea gravels were lost to the voids in the dump. In one instance 100 times the volume of cuttings excavated was backfilled to bring the material to the required level for sealing. The level of material had to be measured frequently in order to position the sealing between gas sampling tube openings. Measurement of the sand (or pea gravel) level was made by lowering down the hole a measuring tape with an end weight which often got stuck between rocks. Placing the bentonite seals also proved to be very time consuming since bentonite pellets tended to bridge up between the drill casing and the monitoring equipment. Pellets had to be dropped down the hole almost individually to prevent bridging.

Silica sand were preferred in backfilling the holes because of its chemical inactiveness and low porosity. However these fine silica sands very often flowed freely into the voids along the well and did little to bring up the level. In such cases, pea-gravels were used instead, since they were much coarser and therefore more effective in raising the levels.

A similar drilling program was conducted at Mount Washington Mine waste rock in 1988. Originally the drilling team attempted to backfill the well to isolate different gas sampling strata, but due to the enormous loss of filling material (sands and pea-gravels) their backfilling effort was aborted.

In summary, the drilling cost increase was caused by the following factors in order of decreasing importance:

- Prolonged installation time as compared to expected;
- The time spent in drilling separate hols for accommodating pressure probes, which was not accounted for in the original budget;
- Time wasted in redrilling some of the holes;
- Excessive consumption of silica sands and bentonite pellets (lost to dump voids).

4.0 MONITORING RESULTS AND DISCUSSION

4.1 MONITORING INSTRUMENTS AND THEIR PERFORMANCES

Two Omega model 866 digital thermometers supplied locally by R.S.Technical Instruments Ltd. were used for the purpose of temperature-profiling the monitoring well through their entire depth. One was owned by Environment Canada, Environment Protection Service in West Vancouver and was kindly load to us. The other was purchased by the Island Copper Mine. This instrument consisted of a multi-thermistor string and a portable readout device. Thermistors were positioned at two meter intervals starting from one end (which was to be lowered to the bottom of the hole). The other end was to be connected to the readout device. The readout device had a digital LCD and was powered by a battery. Test were made to compare the readout of the two thermometers in the same hole and results obtained were almost identical.

Field experience showed that this instrument required 30 minutes to reach a stable reading (called equilibrium for practical purposes) when brought from one ambient temperature to another. Repeatability was equal or better than 0.2 degrees when the instrument was tested on the same hole in two-hour interval and overnight. Both of these conformed to the manufacturer's specifications.

The gas monitoring was accomplished by use of a Nova Model 305 BD portable CO_2 and O_2 analyzer supplied by Nova Analytical Systems Inc. This instrument was also loaned by EPS to us. The analyzer measures carbon dioxide by infra-red spectrometry and oxygen by electrochemical potential. The precision is 2% of the full scale (or 0.2% in absolute value) for carbon dioxide and 0.5% of the full scale (or 0.1% in absolute value) for oxygen. Half a hour warm-up is required before use. The instrument is powered by a built in battery which when fully charged (24 hours recharging is needed from dead to fully charged) is enough to power a day's operation. Field operation of the analyzer involves the following steps:

1. Fully charge the battery before use.
2. Turn on the analyzer and leave it in the environment in which measurements are to be made half a hour before the first measurement to allow warming up.
3. Calibrate the instrument according to the ambient air, which is assumed to be 20.8% oxygen and 0.8% carbon dioxide.
4. Connect the analyzer's intake tube to a sampling tube and turn on the pump. Allow one minute or slightly longer for the gas sample from the deepest sampling point to reach the analyzer, or slightly shorter time can be allowed for shallower sampling points. Reading will usually stabilize when the gas sample from within the dump has reached the analyzer.

5. Oxygen and carbon dioxide concentrations in percentage are read directly from the analyzer's display.
6. Disconnect the sampling tube and allow some fresh ambient air to be drawn into the instrument while watching the displayed figures change. Then repeat steps 4 - 6 for another sampling tube until all the depths are measured.
7. Turn off the pump. Recalibrate the instrument before proceeding to another monitoring hole. Caution should be exercised to avoid accidentally turning off the power switch, since "warming up" is required each time the instrument is turned off.

Problems during well monitoring measurement included three clogged gas sampling tubes and ice formed inside the sampling tubes in the winter blocking some of the sampling tubes.

There were also some problems with operating the Nova gas analyzer. The ranges of normal operating temperature and humidity were often exceeded in practice. A few carbon dioxide concentrations were greater than 10% upper range limit of the analyzer. The oxygen sensor became non-operative during the monitoring measurement in February, 1990 and therefore the data were incomplete for that date.

4.2 MONITORING RESULTS

Three sets of measurement were carried out in October,1989, November, 1989 and February 1990. The results are presented in Table 3.

4.3 DISCUSSION

General Concepts - Preparation for Discussion

The contents under this heading provide some common grounds and are fundamental for understand the discussions that follow.

The concept of Acid Production of a dump, as conventionally used in the field of acid rock drainage (ARD) refers to the multi-staged process during which: (1) sulfided are oxidized in the presence of oxygen (from air) and water, most of the time with bacteria involved to yield sulfuric acid; (2) a fraction of the sulfuric acid so produced is then neutralized by acid consuming minerals; and (3) the sulfuric acid left after neutralization is flushed out by percolating rain water during the wet season or by ground water and emerges as seeps or goes to the ground water system.

TABLE 3 NORTH WEST DUMP MONITORING

Drillhole NWD #1
(Oct. 16, 1989)

Dist.from Bottom (m)	Temp. (C)	CO2 (%)	O2 (%)
0	15.5	0.2	20.6
2	17.5	0.2	20.5
4	19.9	0.3	20.0
6	20.9	0.5	19.4
8	20.7	1.2	16.8
10	21.1	0.3	19.8
12	20.1	0.3	19.7
14	18.5	0.5	19.4
16	17.8	0.2	20.5
18	17.4	0.2	20.5
20.3			

Drillhole NWD #2
(Oct. 17, 1989)

Dist.from Bottom (m)	Temp. (C)	CO2 (%)	O2 (%)
0	18.6	0.2	20.5
2	21.3	0.3	20.3
4	23.4	1.8	14.7
6	24.5	2.7	12.4
8	24.9	0.6	19.4
10	25.9	0.3	19.8
12	25.0	1.2	1.9
14	21.2	0.3	19.8
16	19.6	0.2	20.4
18	18.4	0.2	20.3
20	13.2	-	-
20.2			

Drillhole NWD #4
(Oct. 17, 1989)

Dist.from Bottom (m)	Temp. (C)	CO2 (%)	O2 (%)
0	21.0	2.1	14.4
2	22.9	1.5	14.8
4	22.6	4.2	0.0
6	21.9	4.2	0.0
8	21.0	6.4	0.0
10	20.1	0.5	20.0
12	18.9	8.0	14.5
14	17.4	*	*
16	16.4	0.2	20.4
18	16.0	0.4	18.6
20	-	0.3	20.4
22	-	0.3	20.1
24.1			

Drillhole NWD #6
(Oct. 17, 1989)

Dist.from Bottom (m)	Temp. (C)	CO2 (%)	O2 (%)
0	10.3	0.2	20.6
2	10.8	0.2	20.6
4	11.0	0.2	20.6
6	11.2	0.2	20.6
8	12.1	0.2	20.7
10	13.4	0.3	20.5
12	10.0	-	-
12.2			

* Sampling tube clogged.

Drillhole NWD #7
(Oct. 17, 1989)

Dist.from Bottom (m)	Temp. (C)	CO2 (%)	O2 (%)
0	16.0	0.8	20.7
2	16.6	0.6	18.7
4	17.4	0.5	19.4
6	18.4	0.4	19.6
8	18.1	2.8	16.4
10	17.4	17.1	0.5
12	16.9	4.2	12.6
14	17.3	0.3	20.1
16	17.1	0.4	19.7
18	13.2	-	-
18.6			

Drillhole NWD #8
(Oct. 16, 1989)

Dist.from Bottom (m)	Temp. (C)	CO2 (%)	O2 (%)
0	18.0	0.4	20.0
2	19.1	0.4	19.8
4	19.2	0.6	18.5
6	18.8	0.7	17.9
8	17.3	1.3	17.4
10	16.2	3.2	12.2
12	15.5	1.3	16.0
14	15.1	0.3	20.0
16	15.5	0.3	20.3
18	15.3	0.3	20.2
19.5			

Drillhole NWD #9
(Oct. 16, 1989)

Dist.from Bottom (m)	Temp. (C)	CO2 (%)	O2 (%)
0	18.9	0.8	17.1
2	19.0	0.9	18.1
4	18.4	2.2	11.5
6	17.1	0.6	18.9
8	16.1	0.9	18.4
10	15.7	0.5	19.9
12	15.1	0.3	20.2
14	15.9	0.3	20.1
16	16.2	0.3	20.0
18	13.9	0.4	19.9
19.2			

Drillhole NWD #1
(Nov. 23, 1989)

Dist.from Bottom (m)	Temp. (C)	CO2 (%)	O2 (%)
0	15.8	0.5	18.8
2	17.8	0.2	20.3
4	20.3	0.5	18.7
6	21.1	0.4	19.5
8	20.8	1.3	17.0
10	21.4	0.3	19.8
12	20.4	0.3	19.6
14	17.9	0.3	19.9
16	16.0	0.2	20.3
18	14.5	0.2	20.3
20.3			

Drillhole NWD #2
(Nov. 23, 1989)

Dist.from Bottom (m)	Temp. (C)	CO2 (%)	O2 (%)
0	18.4	0.2	20.4
2	21.3	0.1	20.7
4	23.4	1.5	14.9
6	24.6	2.5	12.8
8	25.2	0.5	19.5
10	26.4	0.3	19.8
12	25.0	1.6	1.5
14	20.5	0.2	20.2
16	18.0	0.2	20.5
18	15.7	0.2	20.5
20.2			

Drillhole NWD #4
(Nov. 23, 1989)

Dist.from Bottom (m)	Temp. (C)	CO2 (%)	O2 (%)
0	19.6	2.6	10.7
2	22.7	1.8	12.1
4	23.0	4.3	0.7
6	22.2	4.3	0.1
8	21.3	4.2	0.1
10	20.5	0.4	20.2
12	19.2	7.6	14.4
14	18.0	*	*
16	16.8	0.2	20.4
18	15.1	0.3	19.1
20	14.1	0.2	20.6
22	13.5	0.2	20.6
24.1	6.6		

* Sampling tube clogged.

Drillhole NWD #6
(Nov. 23, 1989)

Dist.from Bottom (m)	Temp. (C)	CO2 (%)	O2 (%)
0	12.6	*	*
2	12.0	0.1	20.7
4	12.3	0.1	20.7
6	12.5	0.1	20.7
8	12.6	0.2	20.8
10	11.2	0.2	20.7
12	6.1	-	-
12.2	6.1		

* Sampling tube clogged.

Drillhole NWD #7
(Nov. 23, 1989)

Dist.from Bottom (m)	Temp. (C)	CO2 (%)	O2 (%)
0	16.0	0.1	21.7
2	17.2	0.8	19.4
4	18.0	0.4	19.6
6	18.6	0.4	19.6
8	18.6	3.1	17.2
10	18.0	16.4*	1.9*
12	17.4	2.5	14.6
14	17.7	0.2	20.4
16	15.6	0.4	19.9
18	8.6	-	-
18.6	5.7		

Drillhole NWD #8
(Nov. 23, 1989)

Dist.from Bottom (m)	Temp. (C)	CO2 (%)	O2 (%)
0	18.8	0.4	20.0
2	20.1	0.5	19.6
4	19.9	0.6	18.7
6	20.3	1.0	15.5
8	18.6	1.3	17.3
10	17.4	2.9	13.3
12	16.8	0.8	17.7
14	16.4	0.3	20.2
16	16.2	0.2	20.3
18	12.1	0.2	20.5
19.5			

* Interpolated data from previous data set.

Drillhole NWD #9
(Nov. 23, 1989)

Dist.from Bottom (m)	Temp. (C)	CO2 (%)	O2 (%)
0	19.1	0.4	20.2
2	19.1	1.1	17.9
4	18.0	2.1	11.0
6	17.2	0.6	19.1
8	16.9	0.9	18.9
10	16.9	0.7	17.3
12	15.8	0.3	20.3
14	15.8	0.3	20.2
16	15.4	0.3	20.2
18	10.5	0.3	20.2
19.2	9.1		

Drillhole NWD #1
(Feb. 13, 1990)

Dist.from Bottom (m)	Temp. (C)	CO2 (%)	O2 (%)
0	16.5	0.2	20.5
2	18.3	0.2	20.6
4	20.5	0.2	20.4
6	21.3	0.5	19.5
8	20.6	1.1	17.0
10	21.1	0.2	20.3
12	19.2	0.3	20.1
14	16.0	0.3	19.8
16	13.4	0.2	20.4
18	13.5	0.2	20.5
20.3			

Drillhole NWD #2
(Feb. 13, 1990)

Dist.from Bottom (m)	Temp. (C)	CO2 (%)	O2 (%)
0	17.8	0.2	20.5
2	20.6	0.4	20.1
4	23.0	1.5	15.2
6	24.3	2.5	13.5
8	25.3	0.5	19.5
10	25.9	0.3	20.1
12	24.0	2.0	1.7
14	20.1	0.2	20.3
16	16.5	0.2	20.6
18	14.4	0.2	20.6
20.2	8.5		

Drillhole NWD #4
(Feb. 13, 1990)

Dist.from Bottom (m)	Temp. (C)	CO2 (%)	O2 (%)
0	18.7	1.5	15.3
2	22.2	0.2	20.7
4	22.5	4.6	0.4
6	22.1	4.6	0.3
8	21.2	4.0	0.4
10	20.3	0.4	19.9
12	19.1	7.8	15.2
14	18.0	*	*
16	15.8	0.3	20.1
18	12.7	0.3	20.0
20	10.3	0.1	20.8
22	10.6	0.2	20.7
24.1	5.8		

* Sampling tube clogged.

Drillhole NWD #6
(Feb. 13, 1990)

Dist.from Bottom (m)	Temp. (C)	CO2 (%)	O2 (%)
0	10.9		
2	9.6		
4	10.2		
6	10.7		
8	10.5		
10	6.6		
12	0.8		
12.2			

* Sampling tube clogged.

Drillhole NWD #7
(Feb. 13, 1990)

Dist.from Bottom (m)	Temp. (C)	CO2 (%)	O2 (%)
0	16.5	0.1	20.6
2	17.7	0.4	19.9
4	18.5	0.3	20.0
6	18.7	0.3	20.2
8	18.2	2.2	18.3
10	17.5	*	*
12	15.6	1.4	15.1
14	15.5	0.2	20.7
16	11.3	0.4+	19.8+
18	4.4		
18.6			

+ Average of previous two data sets.
* Sampling tube clogged.

Drillhole NWD #8
(Feb. 13, 1990)

Dist.from Bottom (m)	Temp. (C)	CO2* (%)	O2* (%)
0	17.6		
2	18.9	0.5	19
4	18.6		
6	19.4		
8	18.3		
10	16.8		
12	15.4	0.5	18.5
14	14.4	0.2	20.5
16	13.5		
18	8.3		
19.5			

*These data are not reliable, since sampling tubes are suspected to be plugged by ice.

Drillhole NWD #9
(Feb. 13, 1990)

Dist.from Bottom (m)	Temp. (C)	CO2 (%)	O2 (%)
0	17.9		
2	18.9		
4	17.9		
6	17.2		
8	16.9		
10	16.4		
12	14.2		
14	14.3		
16	13.2		
18	6.7		
19.2			

Oxidation refers to the process during which the sulfur in sulfide minerals is chemically transformed into sulfuric acid by passing electrons to oxygen.

Neutralization is defined as the process during which the sulfuric acid produced by oxidation reacts with acid-consuming materials to form sulfate salts (calcium sulfate in the case of calcite being the acid consuming mineral, for example) and water.

We will use the above terms according to their definitions given above in our discussion. For instance, we will not refer the formation of sulfuric acid by oxidation as "acid production".

Many physical and chemical parameters can help us understand the various mechanisms in acid production. Physical and chemical parameters commonly used in acid production studies include: temperature of a dump at various locations; oxygen and carbon dioxide concentrations at various locations of a dump; sulfur- and iron-oxidizing bacteria population densities of solid samples at various locations of a dump and in seeps; redox potential, conductivity, pH, acidity and alkalinity of seeps; total iron concentration and ferric to ferrous iron ratio in seeps; calcium and magnesium ion concentrations in seeps; heavy metal ion concentrations in seeps; and so on.

It is beneficial to classify these parameters into some categories that are meaningful in acid production studies. In this report, we will classify them into three categories: Oxidation indicators, Neutralization indicators and Acid Production Indicators. An indicator is a physical or chemical parameter that measures a process's certain characteristic and that varies according to the speed or progression of that process. Under each category, we will further divide the indicators into two subgroups: Rate Indicators and Accumulation Indicators. Oxidation Rate Indicators measure the rate of oxidation of the moment at measurement while Oxidation Accumulation Indicators measure the amount of species accumulated since the oxidation began. For example, oxygen concentration can serve as an oxidation rate indicator, because the local oxygen concentration is a result of an equilibrium between oxygen consumption by oxidation and diffusion of oxygen from other areas where oxygen concentration is higher. When the oxidation slows down, the equilibrium will shift to a higher oxygen concentration. Soluble sulfate concentration of a dump sample can serve as an oxidation accumulation indicator, since sulfate (solid when dry) will not migrate on dry solids and therefore accumulates at the spots of oxidation until a major rainstorm comes to dissolve and carry it away. Therefore, at the end of a rainless period, the sulfate quantity reflects the results of oxidation products accumulation for that period.

Rate indicators are usually diffusive parameters, such as temperature, pressure, and gas concentrations. The distribution of these parameters always change to homogenize whenever there is a gradient. A equilibrium is reached at steady states. Accumulation indicators are usually massive parameters such as mass, thickness, volume and area.

Meanings of the neutralization rate indicator and neutralization accumulation indicator are more or less similar. It is difficult to find an appropriate neutralization rate indicator in an dry dump environment, however, for the following reasons: First, neutralization reaction rate is usually much faster than oxidation rate so that concentrations of gas produced by neutralization acutally reflect the rate of oxidation. Second, neutralization reactions usually do not produce or absorb much heat, so they have litte effect on temperature. An example of neutralization rate indicator is the pH in the vicinity of a lump of calcite immersed in an infinite volume of weak acid solution. As to acid production, it is a little different from the previous two processes in that it is a result of three processes: oxidation, neutralization and flushing by rain (or ground) water. Total acidity and pH of seeps are examples of acid production rate indicator.

Some samples of each classification are given below.

Oxidation	Rate Indicator:	Temperature, carbon dioxide concentration, oxygen concentration, local redox potential, bacteria population density
	Accumulation Indicator:	Sulfate salts of dump samples, Total soluble iron of dump samples

Neutralization	Rate Indicator:	Carbon dioxide concentration
	Accumulation Indicator:	Soluble calcium of dump samples
Acid Production	Rate Indicator:	pH, total acidity (alkalinity), heavy metal ion concentrations in seeps, etc.
	Accumulation Indicator:	Total acidity released to the environment in a period of time. Total release of some heavy metals in a period of time, etc.

The carbon dioxide concentration can be either an oxidation rate indicator or a neutralization rate indicator depending on the relative reaction speed of oxidation and neutralization. If the oxidation rate is much slower than the neutralization rate, then carbon dioxide concentration is an oxidation rate indicator. Otherwise, it is a neutralization rate indicator. In the former case, whenever sulfuric acid is produced, it is immediately neutralized by carbonaceous minerals, and the carbon dioxide concentration should correlate well with oxygen concentration because both are oxidation indicators.

The oxidation reaction of pyrite (and some other sulfides) is very exothermic while neutralization reactions usually involve less heat consumption or generation so that the effect of chemical reactions on the local temperature is primarily that of sulfide oxidation. Therefore, temperature is an oxidation indicator too. However, the situation is complicated by the heat exchange between the dump and the atmosphere, which is probably responsible for the lack of agreement between temperature and gas concentrations (carbon dioxide and oxygen) (see below under Relationship between Monitored Parameters).

The selection of indicators to use in monitoring a waste dump can not be arbitrary. It is limited by cost of monitoring well construction and availability of measuring instruments in the market. In our monitoring program, temperature, oxygen and carbon dioxide concentrations were chosen. These are all oxidation rate indicators. Pressure probes were planned but yet to be completed.

The temperature at a certain depth is affected by many factors, the most important ones of which are perhaps heat production by oxidation, temperature fluctuation in various seasons, cooling by percolating rain water and heat carried by convectional air. Oxygen and carbon dioxide concentrations are probably controlled by the chemical reaction at the locality measured and convection and diffusion of gas from other areas to the area concerned.

Because of the complexity of the processes controlling these parameters, it is almost impossible to predict them theoretically. By monitoring the variations of these parameters, however, we can infer the major processes in the dump that controls these parameters and thus acquire an understanding of how these parameters are related to acid production in the dump.

Acid-base accounting is a technique to quantify the potential of acid production by balancing the capacity of oxidation with that of neutralization of a waste rock material using simple laboratory static analysis. Roughly speaking, Acid Producing Potential (APP) is the amount of sulfuric acid generated if all sulfur (all assumed inorganic and in reduced form) were to be oxidized to sulfuric acid. Acid Consuming Potential (ACP) is the amount of calcium carbonate equivalent of a waste material. Net Neutralizing Potential is the difference of ACP and APP while Net Producing Potential is the difference of APP and ACP. Theoretically speaking, there should likely be some correlation between APP and oxidation indicators, between ACP and neutralization indicators and between NNP and acid production indicators, although the indicators reflect dynamic properties.

Since temperature, oxygen and carbon dioxide concentrations are all oxidation indicators, they should all correlate to Acid Producing Potential, rather than to Net Producing Potential (or Net Neutralizing Potential). One should bear this point in mind when reading the following discussions.

Monitoring Results and Acid-base Accounting

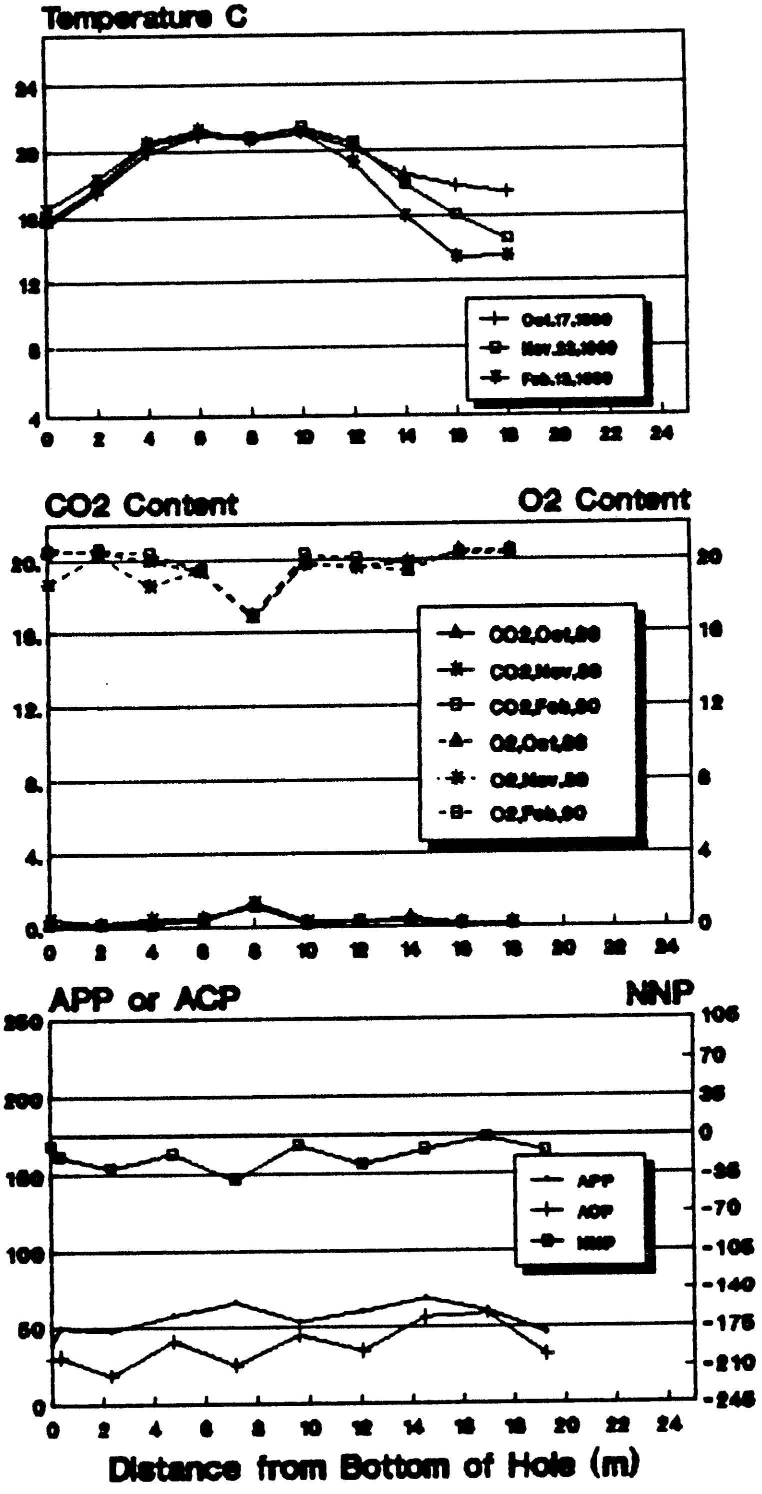
Figures 24 through 30 integrated all monitoring results and the acid-base accounting results and plotted theses parameters against the distance from the bottoms of the holes.

Examination of these graphs reveals the following:

- Oxygen and carbon dioxide concentration readings are very similar for the three sets of data recorded over a five month period, suggesting that the gas concentrations are not significantly affected by change of seasons and that the dump has probably reached a steady state.
- The trends in oxygen and carbon dioxide concentrations corresponds quite well qualitatively for all the graphs: every decrease in oxygen concentration is accompanied by an increase in carbon dioxide. We will look at this correlation quantitatively later in this section.
- Temperature profiles varied visibly with the seasons. If we were to assume that the dump is in a steady state as suggested by the gas concentration profiles, the heat generated by oxidation should also be roughly the same, therefore the temperature changes are

FIGURE 24

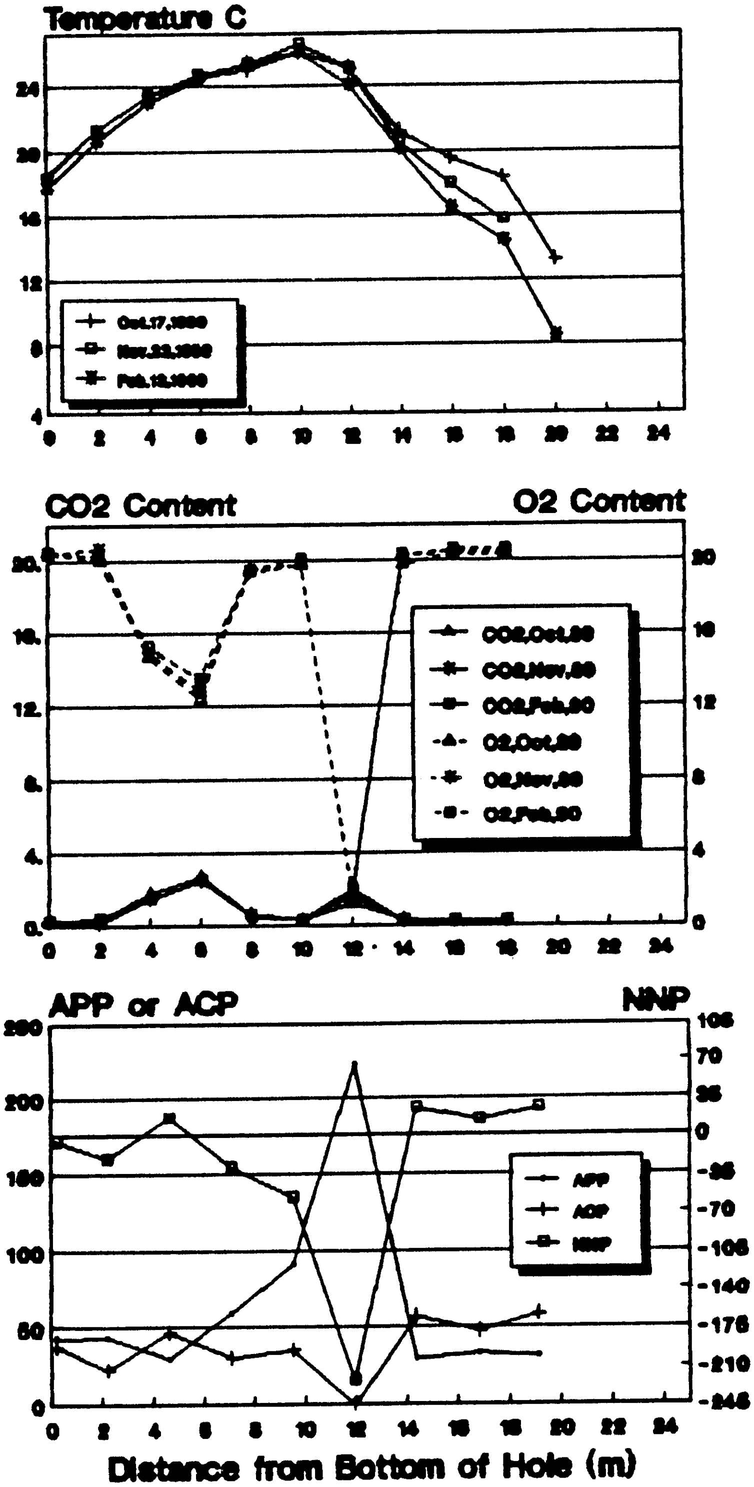
Drillhole NWD #1 Monitoring



ACP,NNP: kg CaCO3/T; APP: kg H2SO4/T

FIGURE 25

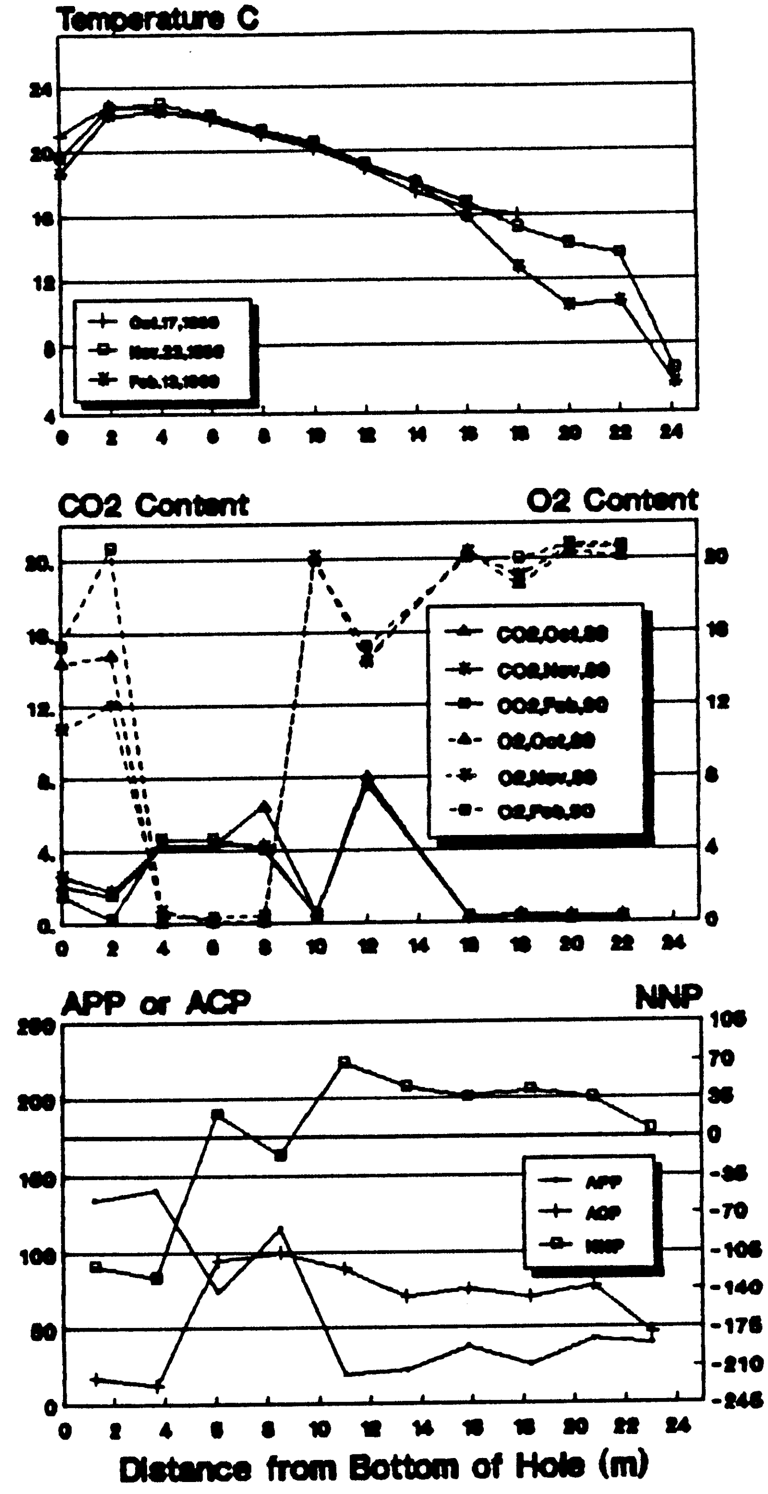
Drillhole NWD #2 Monitoring



ACP,NNP: kg CaCO3/T; APP: kg H2SO4/T

FIGURE 26

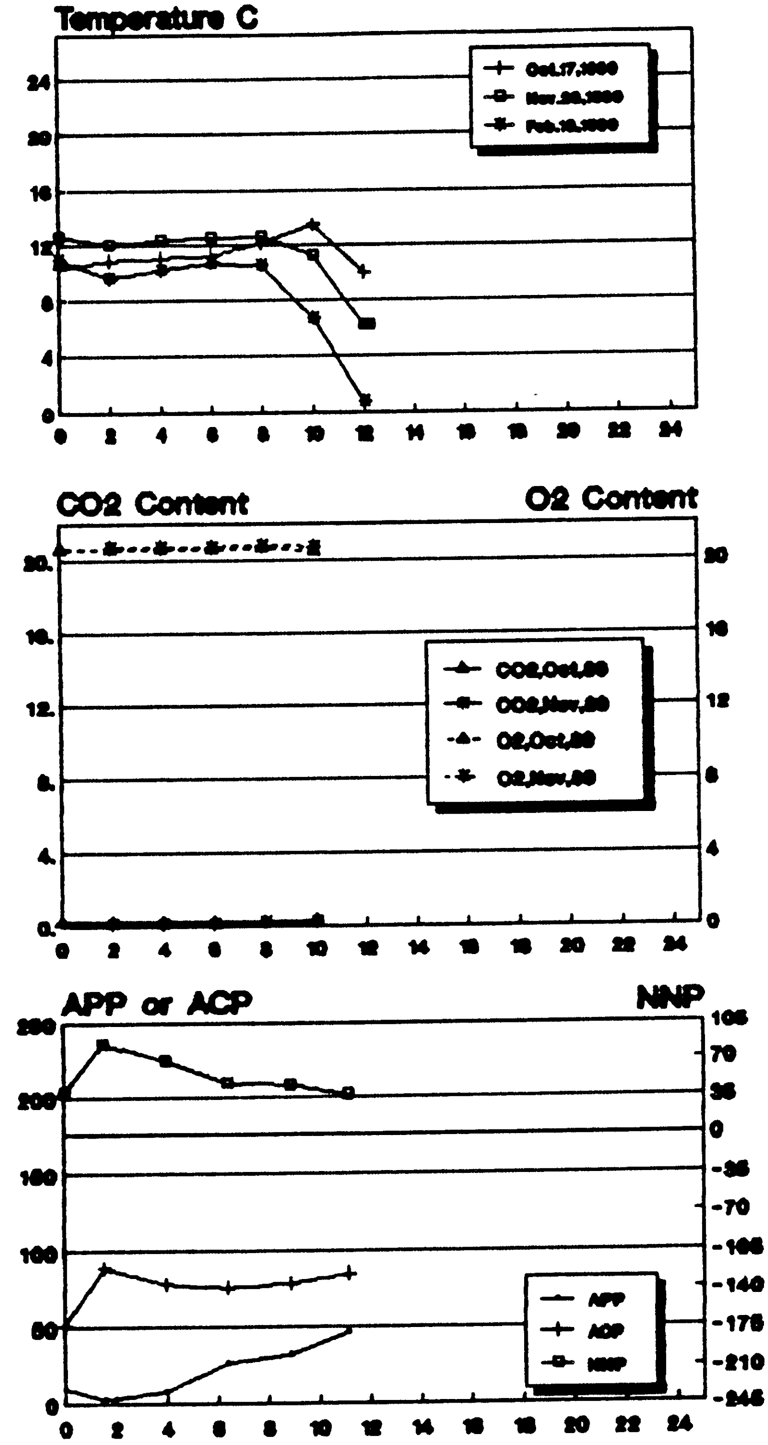
Drillhole NWD #4 Monitoring



ACP,NNP: kg CaCO3/T; APP: kg H2SO4/T

FIGURE 27

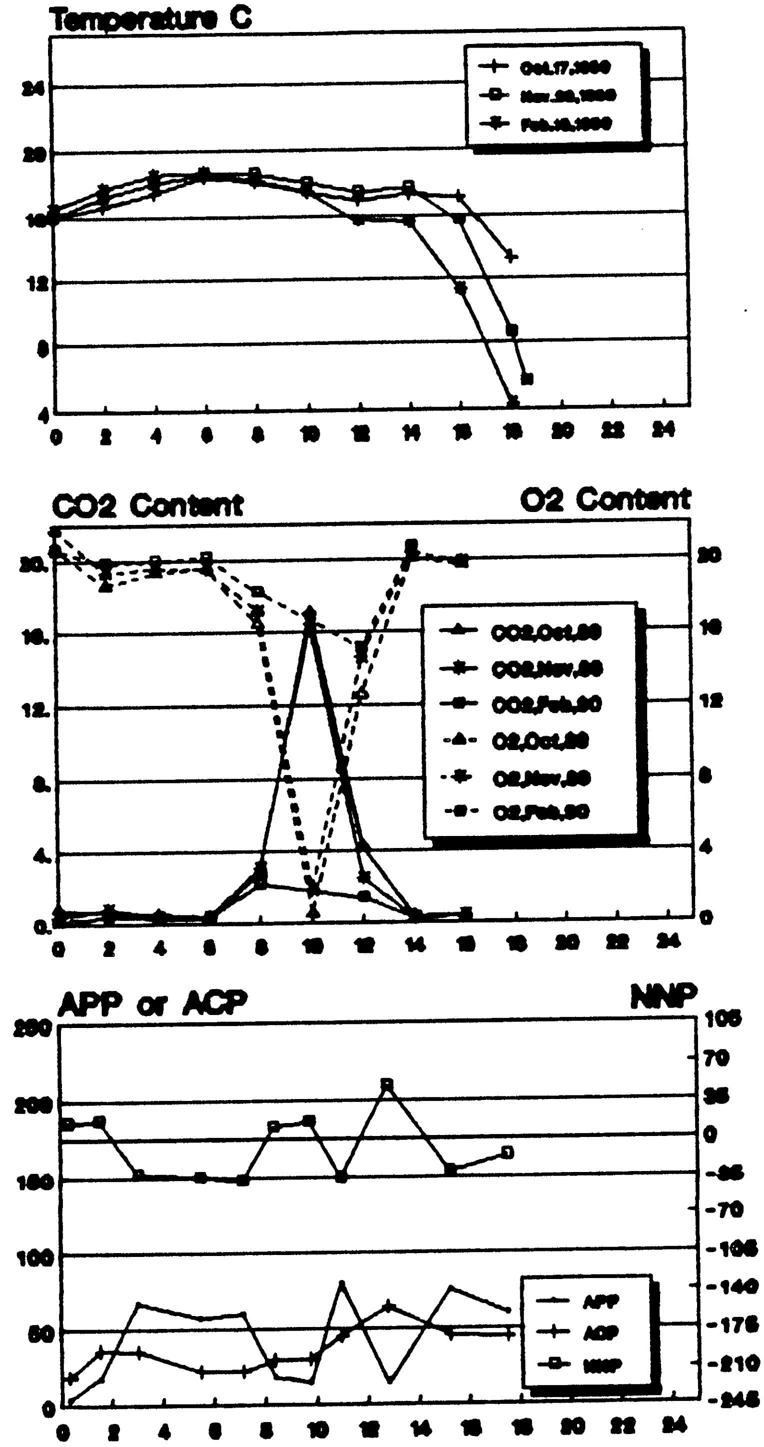
Drillhole NWD #6 Monitoring



ACP,NNP: kg CaCO3/T; APP: kg H2SO4/T

FIGURE 28

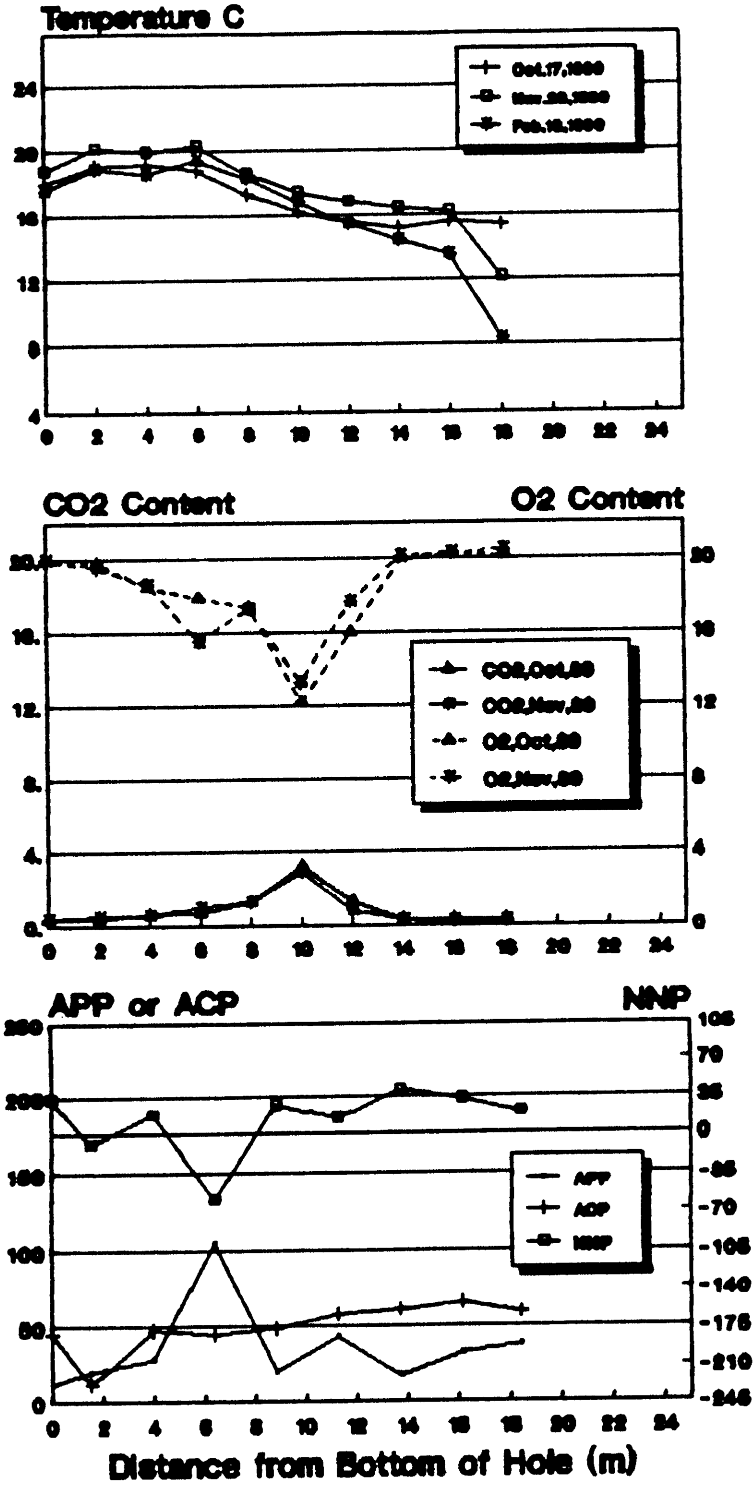
Drillhole NWD #7 Monitoring



ACP,NNP: kg $CaCO_3$/T; APP: kg H_2SO_4/T

FIGURE 29

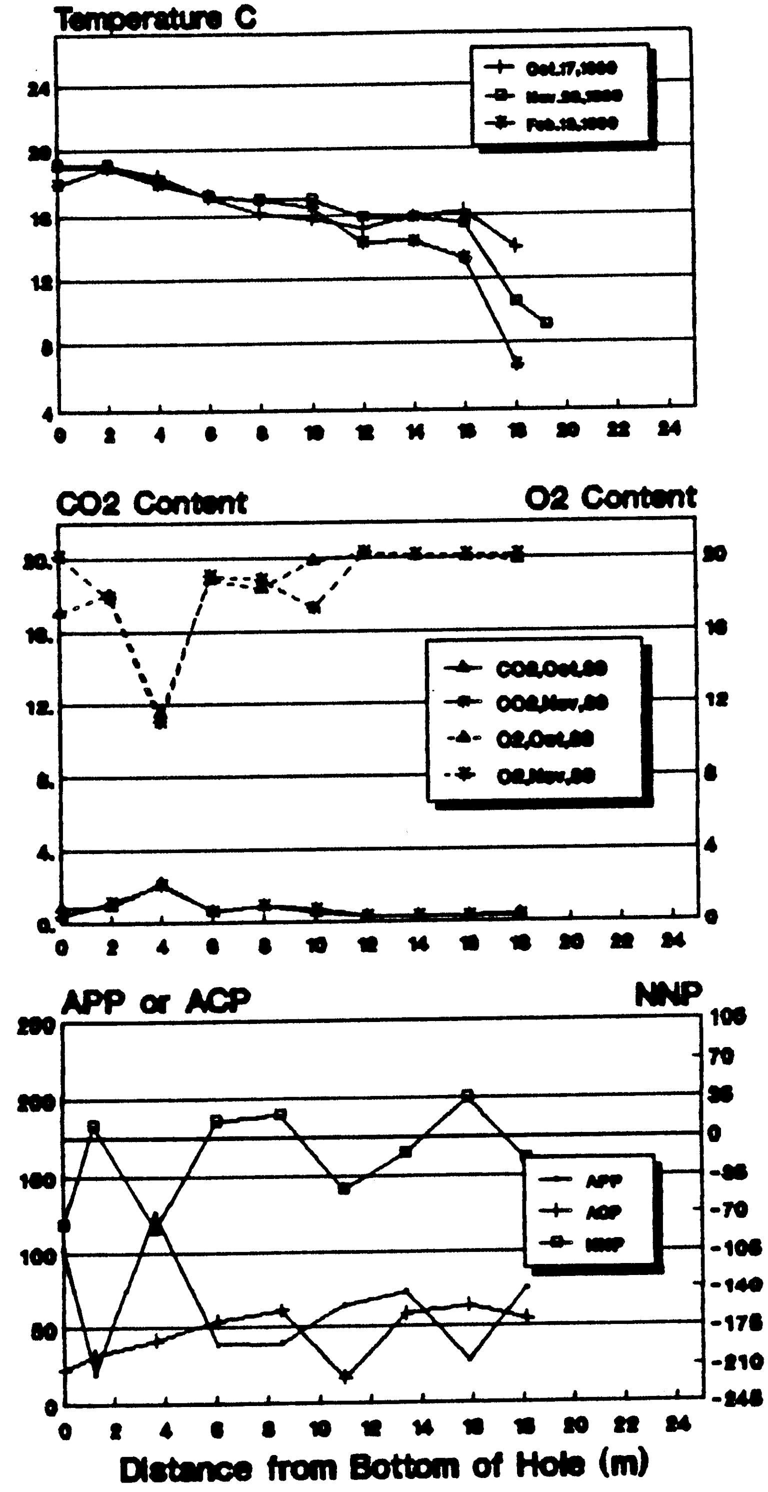
Drillhole NWD #8 Monitoring



ACP,NNP: kg CaCO3/T; APP: kg H2SO4/T

FIGURE 30

Drillhole NWD #9 Monitoring



ACP,NNP: kg CaCO3/T; APP: kg H2SO4/T

solely due to the change of ambient temperature. The temperature profiles will be further discussed later in this section.

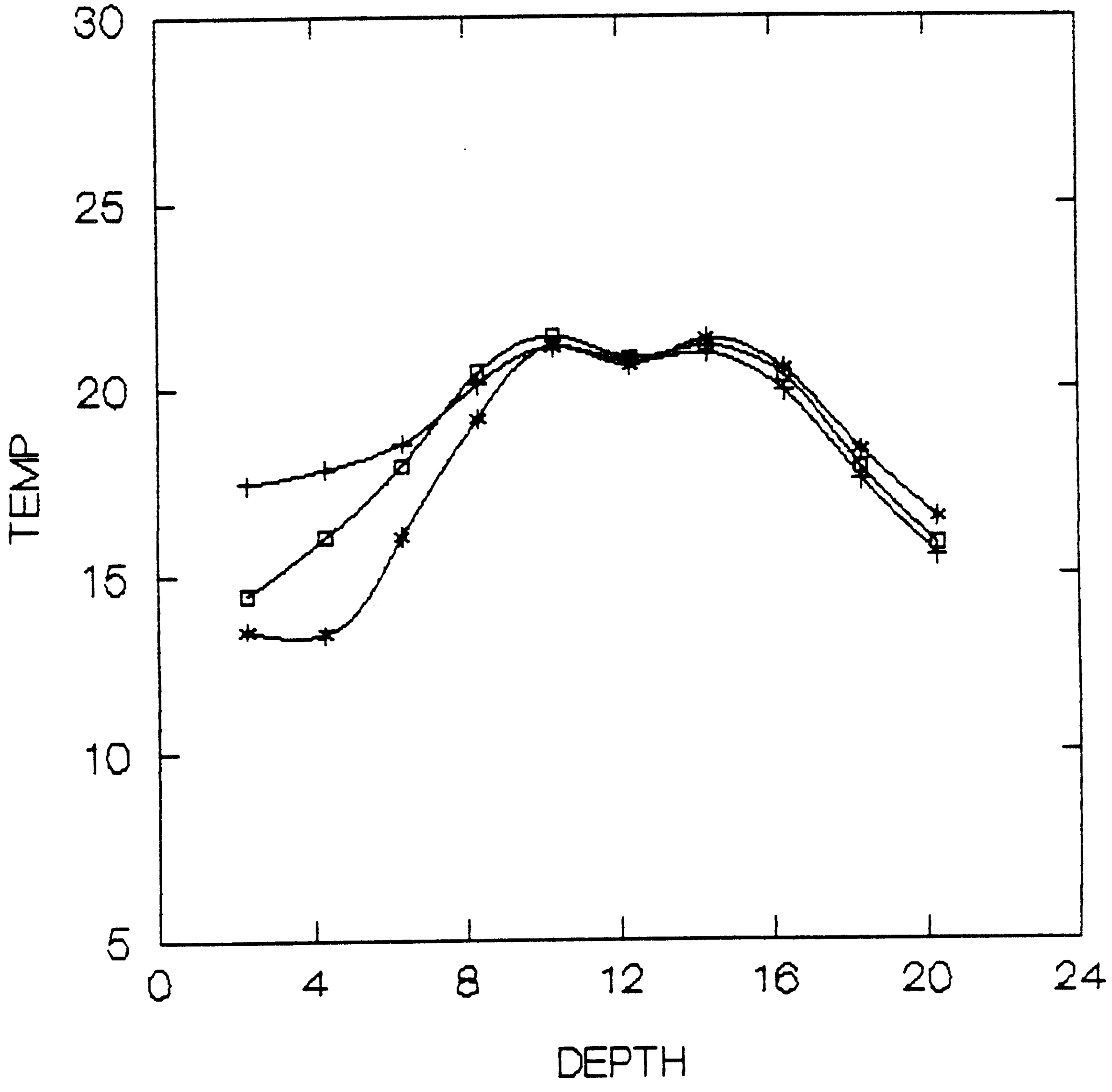
- Gas concentrations relate to acid-base accounting in the following manner: where there is significant decrease in oxygen concentration (or increase in carbon dioxide concentration), there is very likely a increase in APP. But the reverse is not true, that is to say, when APP experiences a sharp increase, there is not necessarily a change in gas concentrations.
- There does not seem to be any correlation between temperature trend and APP. Neither is there present a relationship between temperature and gas concentrations.
- Oxygen and carbon dioxide concentrations varied over a remarkably wide spectrum: oxygen from 0% to 20.8% and carbon dioxide from 0.1% to more than 10%. It is very interesting to compare our data with those obtained in Mount Washington's baseline monitoring. In Mount Washington, carbon idoxide concentration varied from 0.1% to 1.4% and oxygen from 16% to 20.8% (Reference 1).

Temperature Profiles

Temperature profiles are replotted against depth in Figures 31 through 37 instead of against distance from bottom as in Figures 24 through 31.

FIGURE 31

TEMPERATURE PROFILE FOR WELL NWD#1

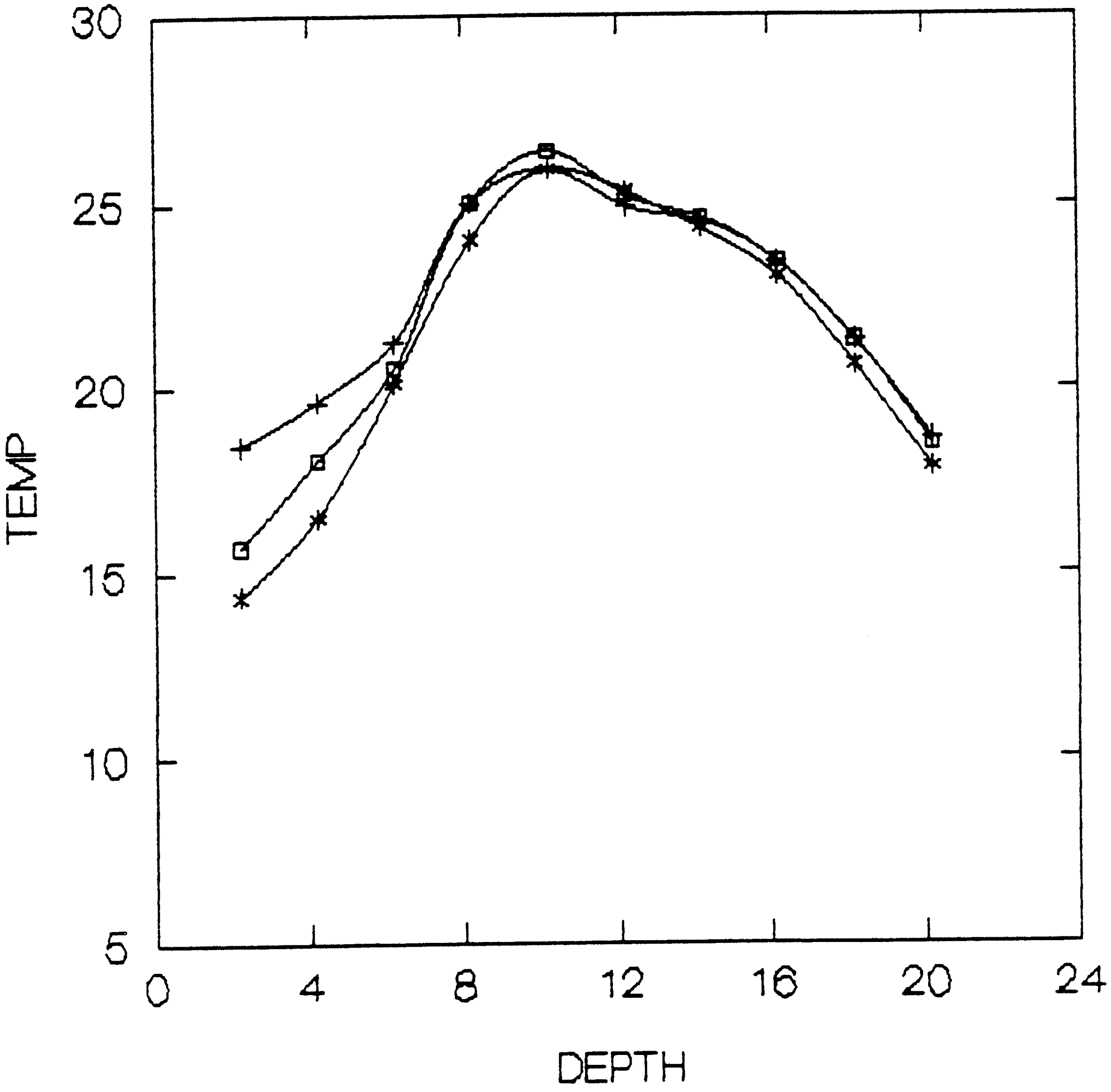


PLUS SIGN - OCT,1989 SQUARE - NOV,1989 STAR - FEB,1990

AMBIENT TEMPERATURE: OCT. 1989 - 12°C NOV. 1989 - 9°C FEB. 1990 - -2°C

FIGURE 32

TEMPERATURE PROFILE FOR WELL NWD#2

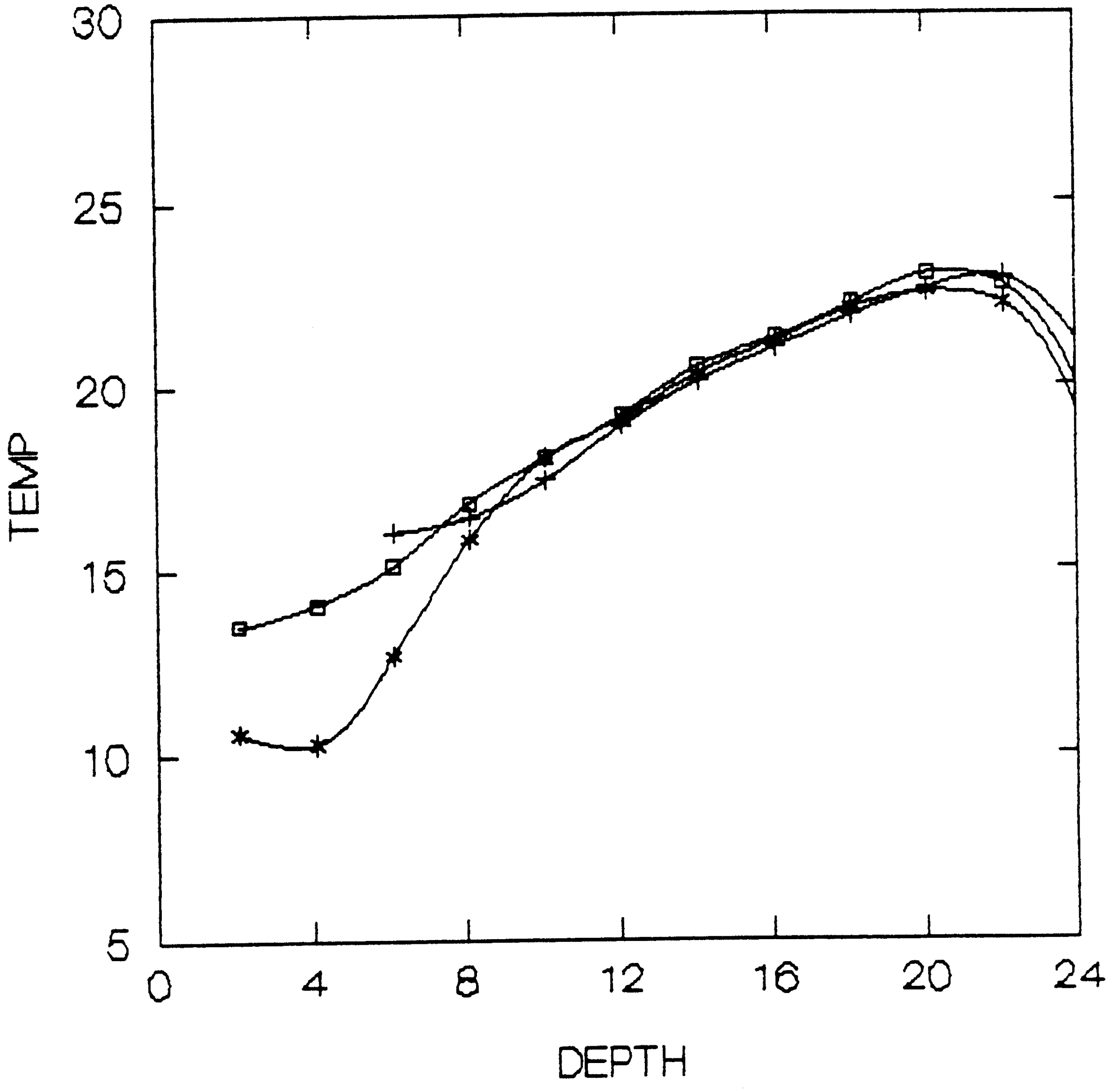


PLUS SIGN - OCT, 1989 SQUARE - NOV, 1989 STAR - FEB, 1990

AMBIENT TEMPERATURE OCT. 89 – 12°C NOV. 89 – 9°C FEB. 90 – -2°C

FIGURE 33

TEMPERATURE PROFILE FOR WELL NWD#4

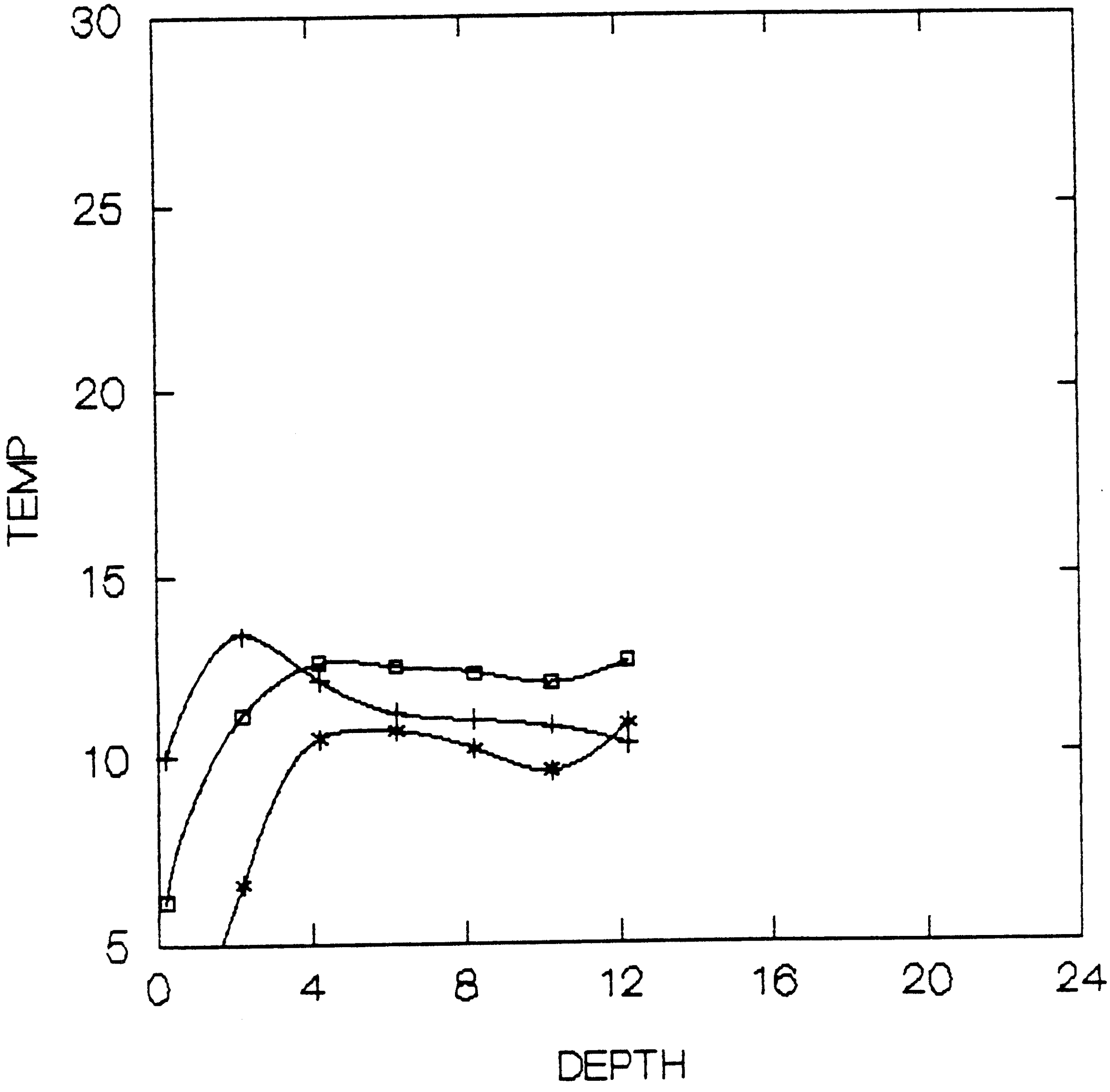


PLUS SIGN - OCT,1989 SQUARE - NOV,1989 STAR - FEB,1990

AMBIENT TEMPERATURE: OCT.89 – 12°C NOV. 89 – 9°C FEB.90 – -2°C

FIGURE 34

TEMPERATURE PROFILE FOR WELL NWD#6

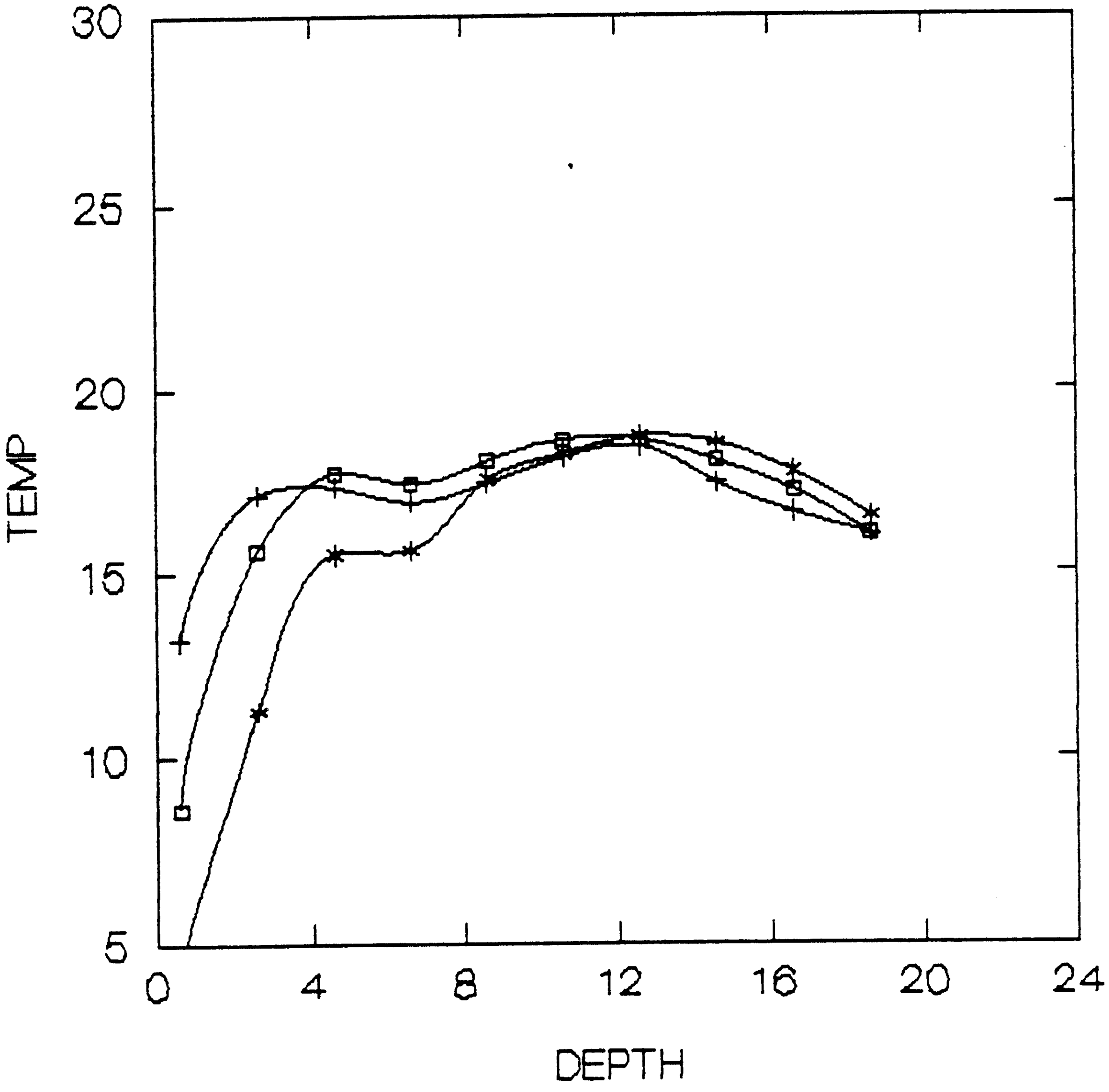


PLUS SIGN - OCT,1989 SQUARE - NOV,1989 STAR - FEB,1990

AMBIENT TEMPERATURE: OCT. 89 - 12°C NOV. 89 - 9°C FEB. 90 - -2°C

FIGURE 35

TEMPERATURE PROFILE FOR WELL NWD#7

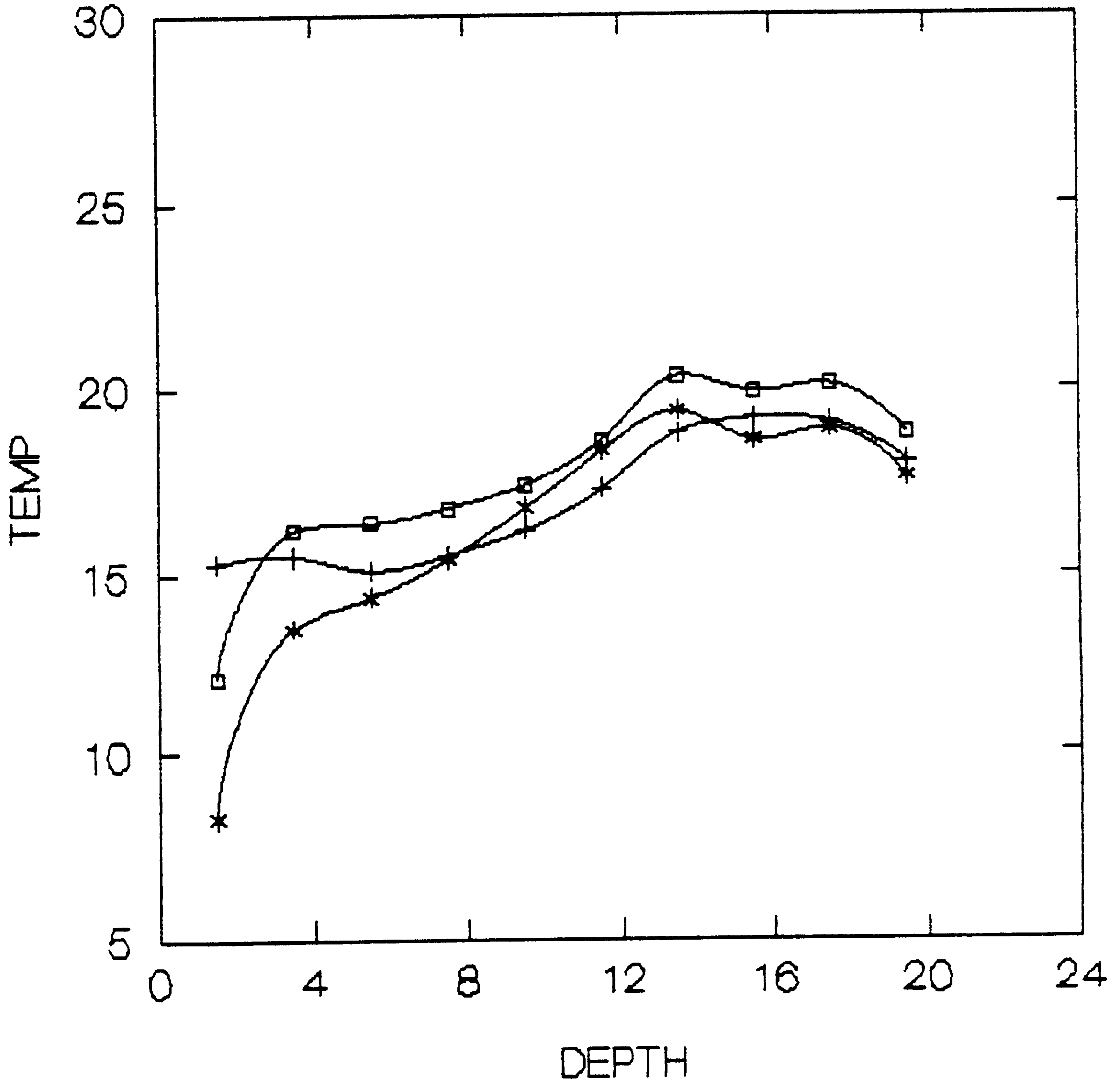


PLUS SIGN - OCT,1989 SQUARE - NOV,1989 STAR - FEB,1990

AMBIENT TEMPERATURE: OCT. 89 - 12°C NOV. 89 - 9°C FEB. 90 - -2°C

FIGURE 36

TEMPERATURE PROFILE FOR WELL NWD#8

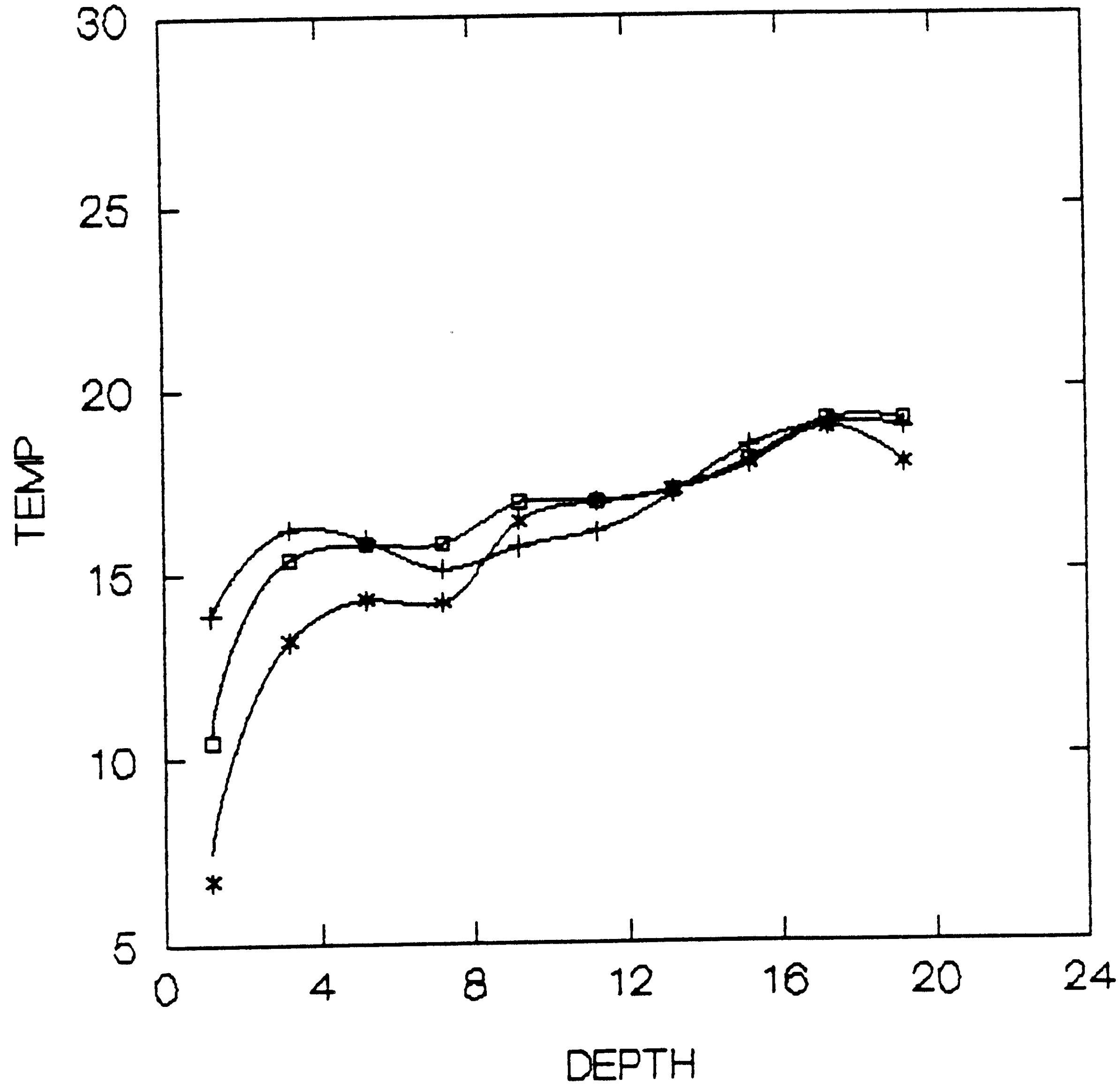


PLUS SIGN - OCT,1989 SQUARE - NOV,1989 STAR - FEB,1990

AMBIENT TEMPERATURE: OCT.89 - 12°C NOV.89 - 9°C FEB.90 - -2°C

FIGURE 37

TEMPERATURE PROFILE FOR WELL NWD#9



PLUS SIGN - OCT,1989 SQUARE - NOV,1989 STAR - FEB,1990

AMBIENT TEMPERATURE: OCT.89 - 12°C NOV 89 - 9°C FEB.90 - -2°C

Although the structures of the temperature profiles are very diversified, some common features can nevertheless be extracted and explanations can be given.

Let us start with drill hole NWD #6 which stands out from the others because it is located on the western slope and is only 12 meters deep (see Figure 19 for location). Since the material throughout the whole depth has small Acid Producing Potentials (Table 2 and Figure 28) it is reasonable to assume that the heat generated by sulfide oxidation can be neglected. Therefore, the variation of the temperature profile is a sole result of the interaction between the dump and the ambient air. It can be seen in Figure 34 that temperatures throughout the whole depth changed with the seasons. Ambient temperatures at the time of measurement were 12 degrees for October,1989, 9 degrees for November 1989 and -2 degrees for February, 1990. The temperature of top four meters of the hole varied synchronously with season while the depth below had a lag in phase and the amplitude of seasonal variation was smaller than that of the ambient air. This reflected the heat preserving capacity of the dump material.

For the rest of the drill holes, the following common features have been noticed:

- The influence of seasonal temperature change penetrated to approximately 10 meters below dump surface (except NWD #8 where the entire column changed with seasons for some unknown reason);

- The top four meters were generally in phase with the seasonal ambient air temperature changes.
- The dump body was always warmer than the ambient air for the seasons we monitored.
- There was a general trend for the temperature changes along the hole: The temperature increased from the surface down, and reached a maximum (or a few local maxima), then fell off towards the bottom. This trend seemed to suggest that the temperature of the dump was affected by some diffusive or convective cold air current travelling along the interface of the dump and original ground.

In conclusion, heat generated by sulfide oxidation certainly contributed to the elevation of temperature within the dump, which probably was the reason why the temperature profiles differed so greatly in shape, even for the holes having similar locations in the dump. However, the temperature profiles were a result of a combined effect of oxidation and seasonal temperature variation, and could not as yet be partitioned into contribution from oxidation and contribution from seasonal temperature variations.

Relationship between Monitored Parameters

To test if there are any correlations between the three monitored parameters in our data, the three parameters, temperature, oxygen concentration and carbon dioxide concentration were plotted in pairs. Figures 38 and 39 are plots of temperature versus oxygen concentration and temperature versus carbon dioxide concentration for October, 1989. The numbers in the plots stand for the drill hole numbers and the exact data point is the centre of the number. It can be seen that the data points are scattered and no correlations were found. This is in agreement with the above discussion we have made.

There seem to be a good linear correlation between oxygen concentration and carbon dioxide concentration. (Figure 40) This correlation can be explained by assuming that the oxidation rate is slower than the neutralization rate thus carbon dioxide concentration becomes an oxidation rate indicator, as is oxygen concentration.

Relationship between APP and Temperature, Oxygen and Carbon Dioxide Concentration

Figures 41 through 43 present APP-temperature plots for October, 1989, November, 1989 and February, 1990. No correlation was observed.

FIGURE 38

TEMPERATURE VS. O2 FOR OCT.,1989

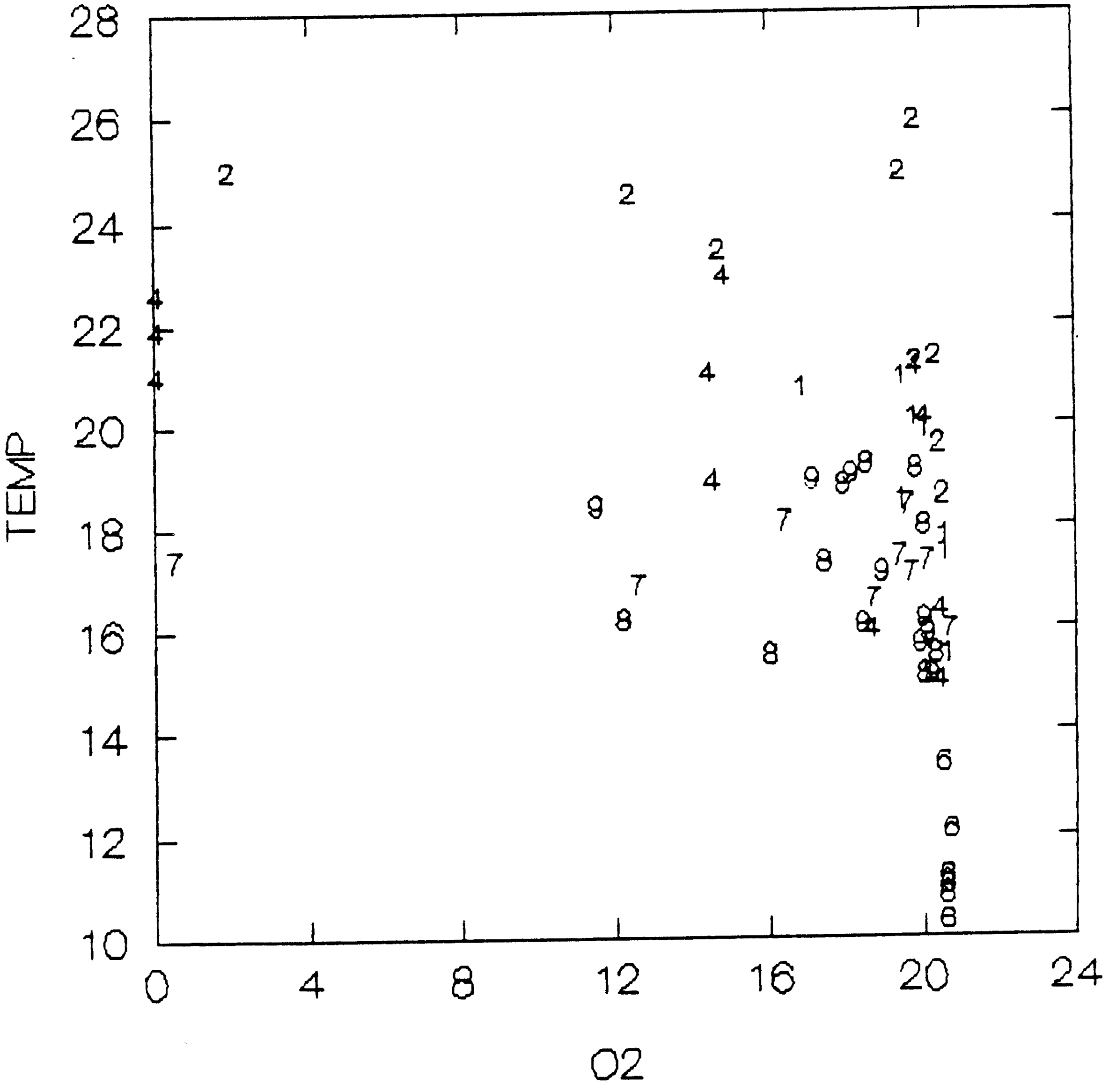


FIGURE 39

TEMPERATURE VS. CO2 FOR OCT., 1989

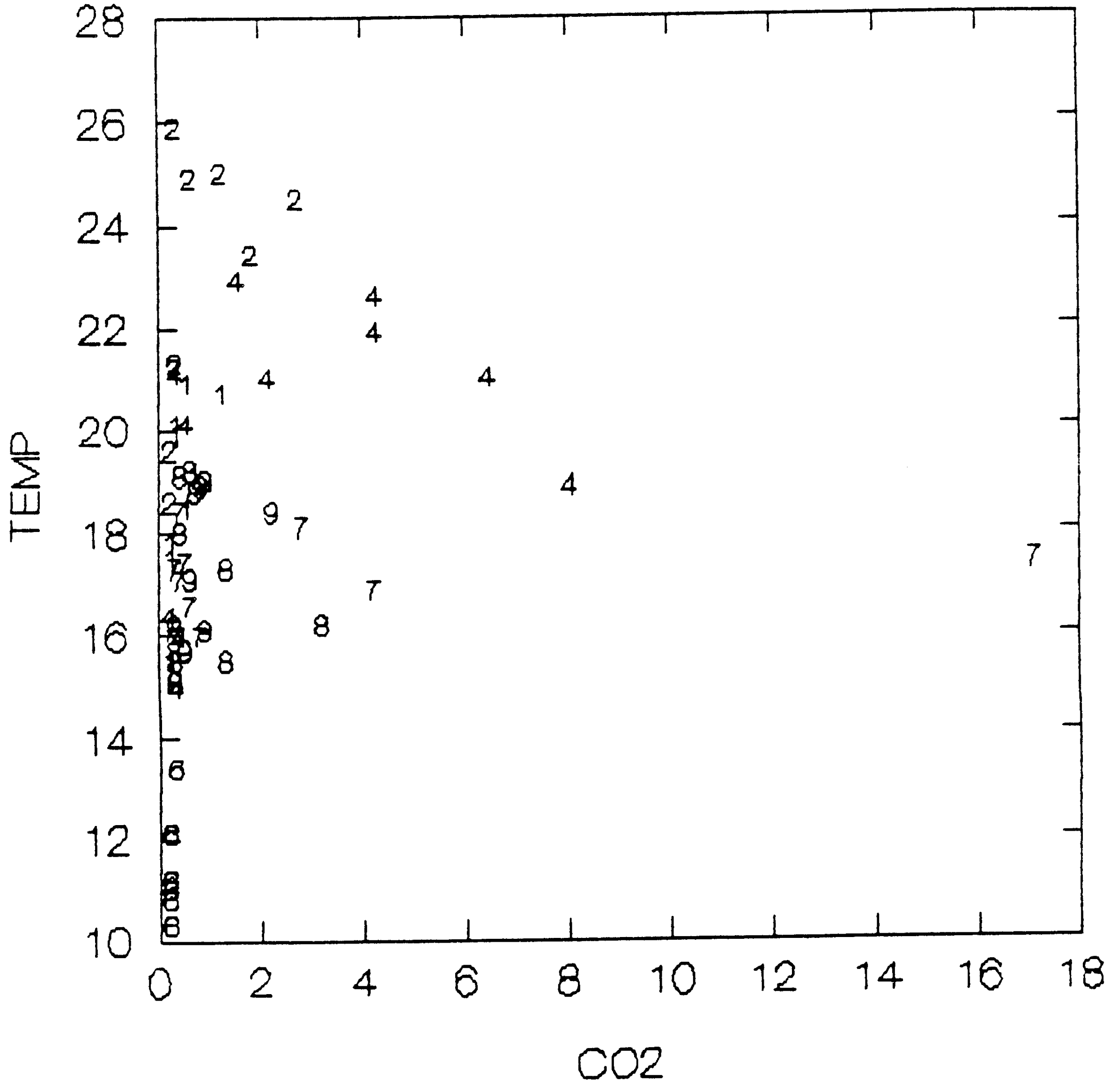


FIGURE 40

CO2 - O2 RELATIONSHIP

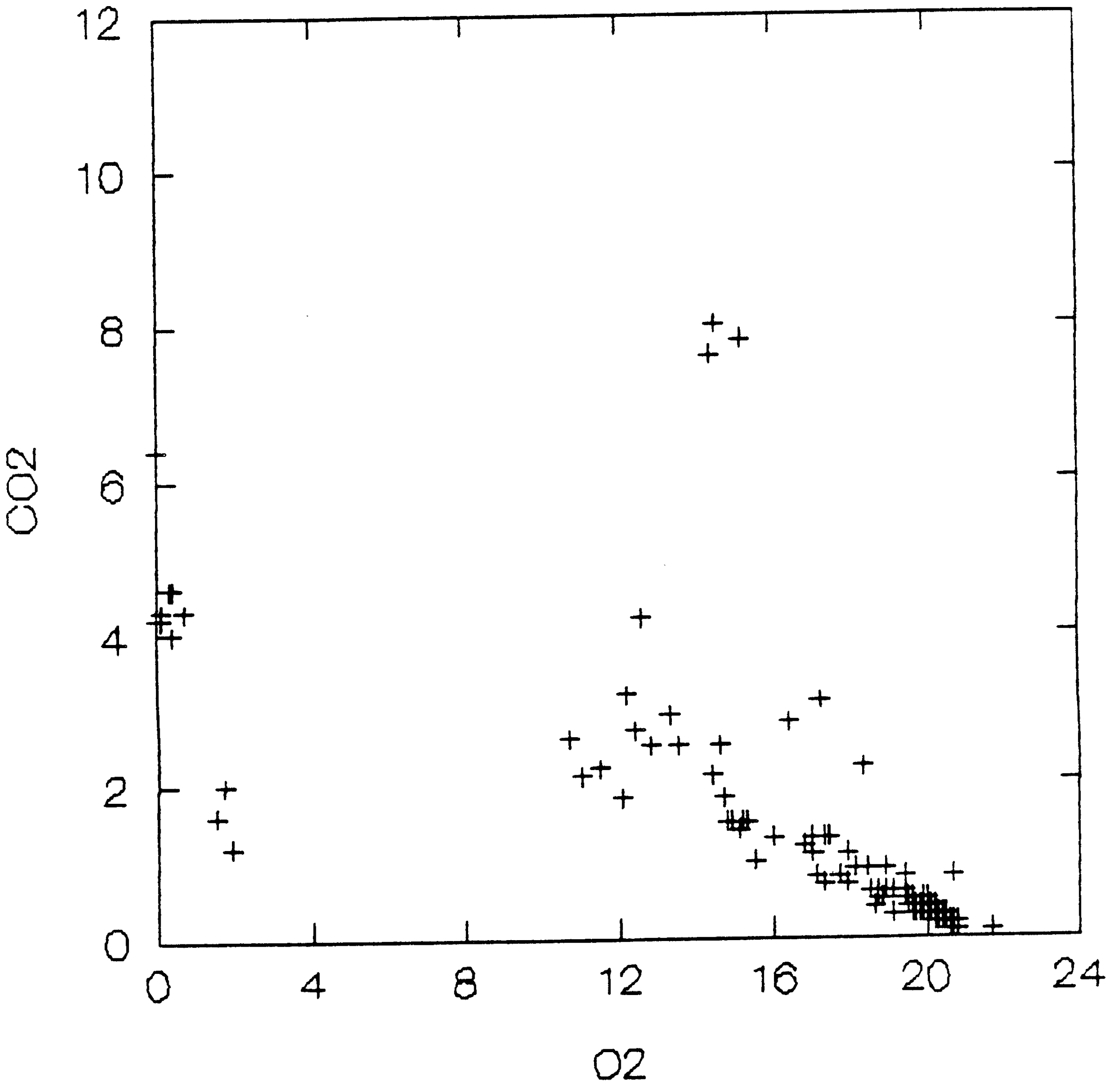


FIGURE 41

APP VS. TEMPERATURE FOR OCT., 1989

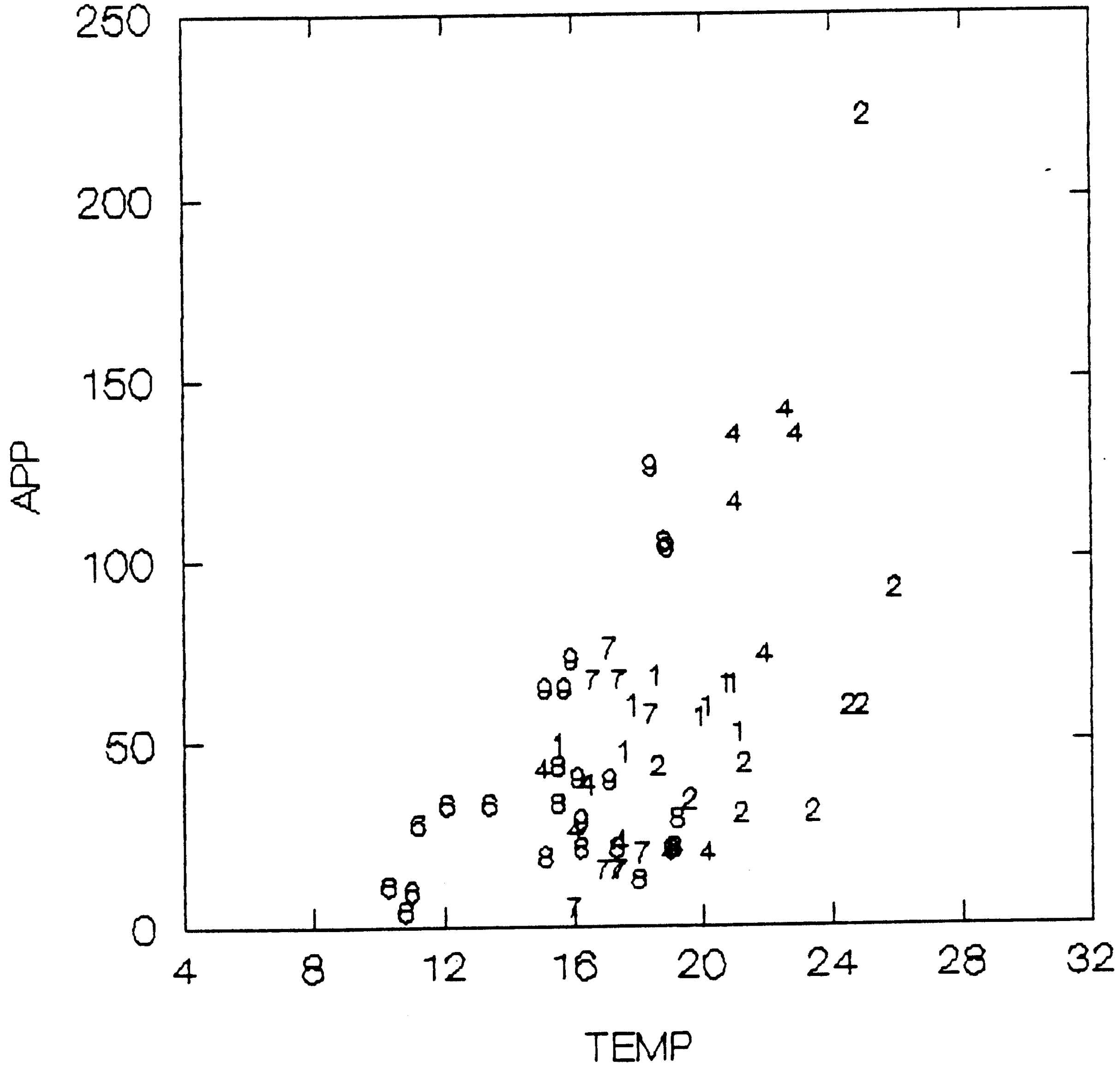


FIGURE 42

APP VS. TEMPERATURE FOR NOV., 1989

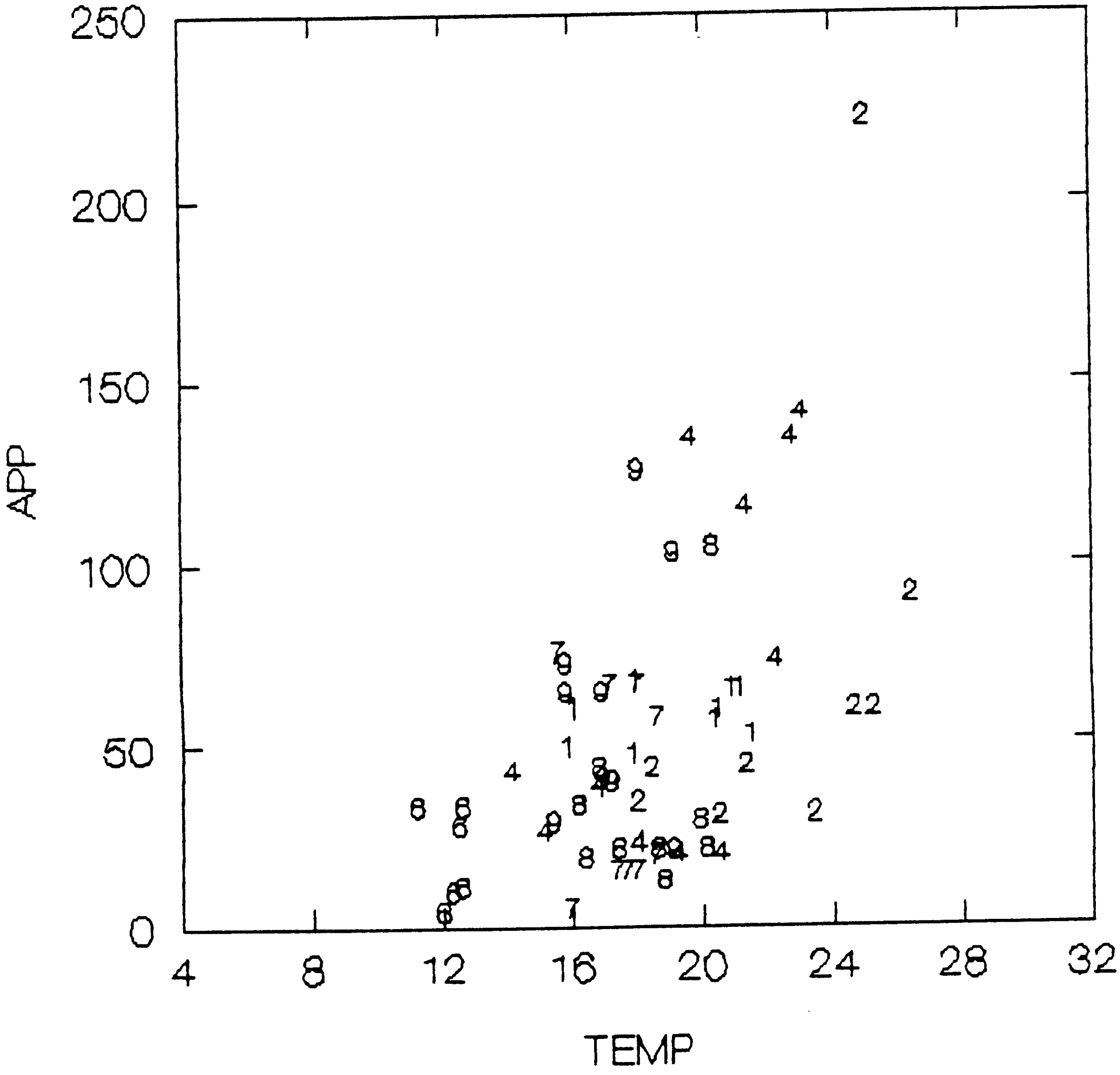


FIGURE 43

APP VS. TEMPERATURE FOR FEB..1990

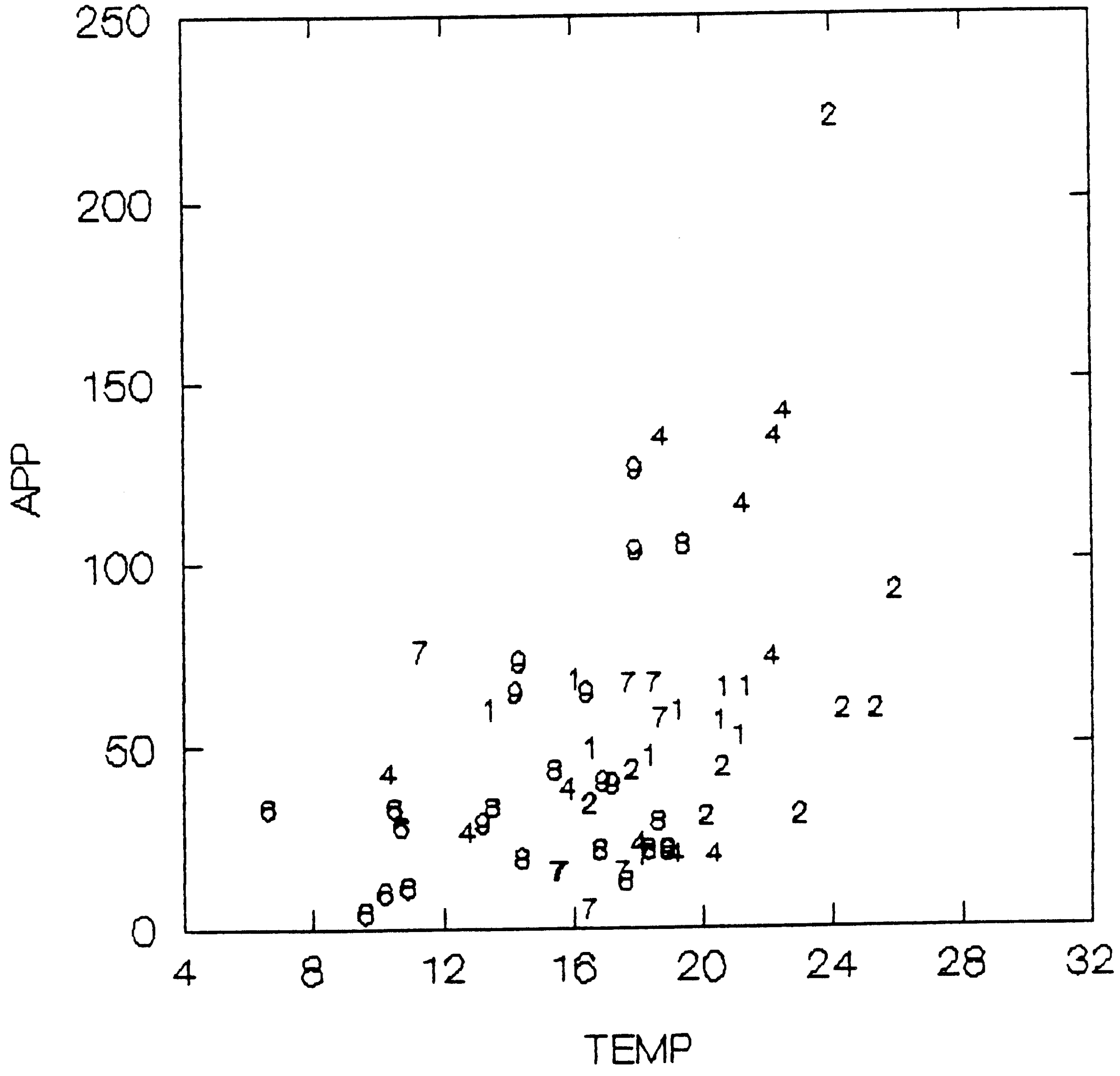
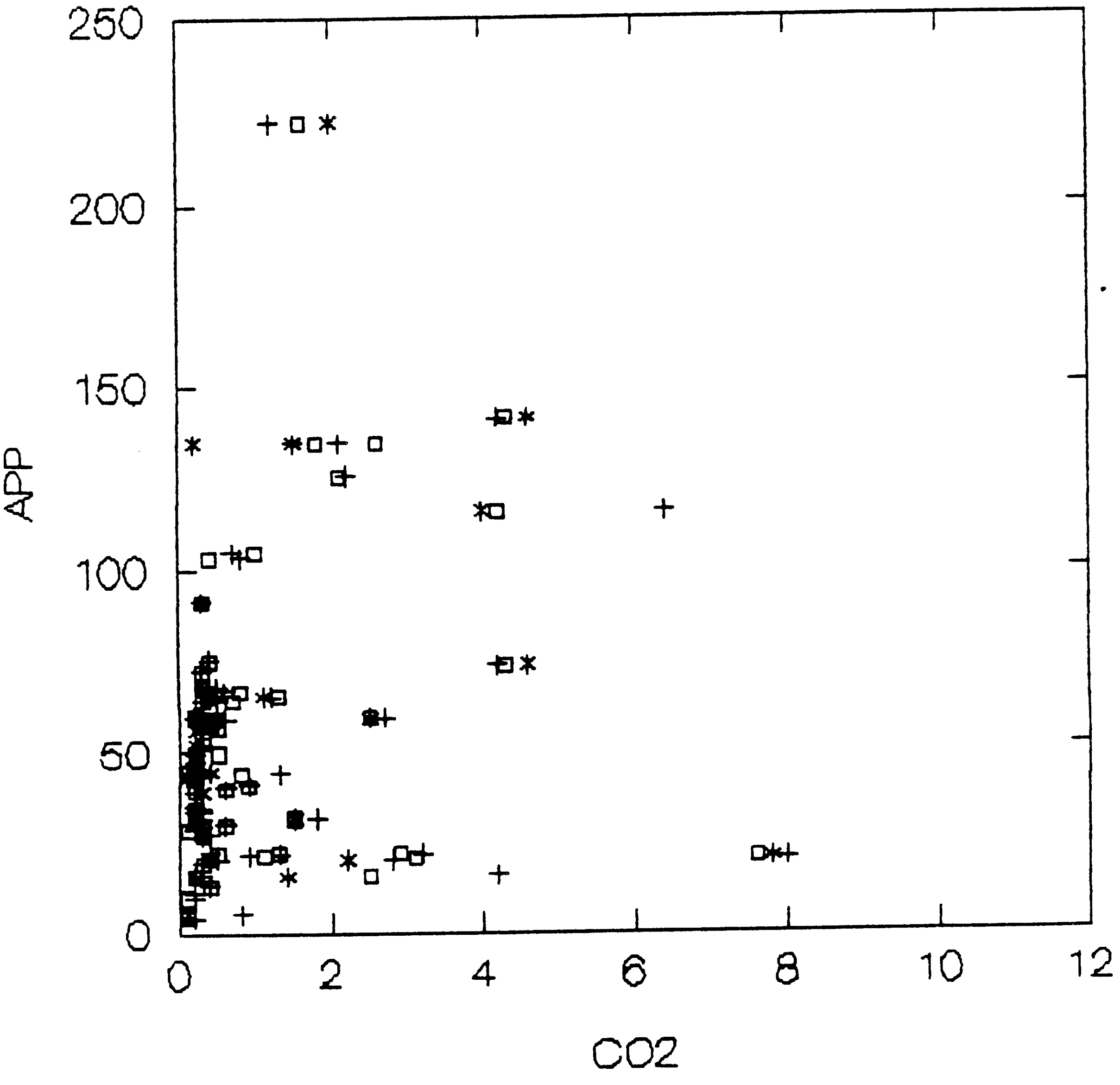


FIGURE 44

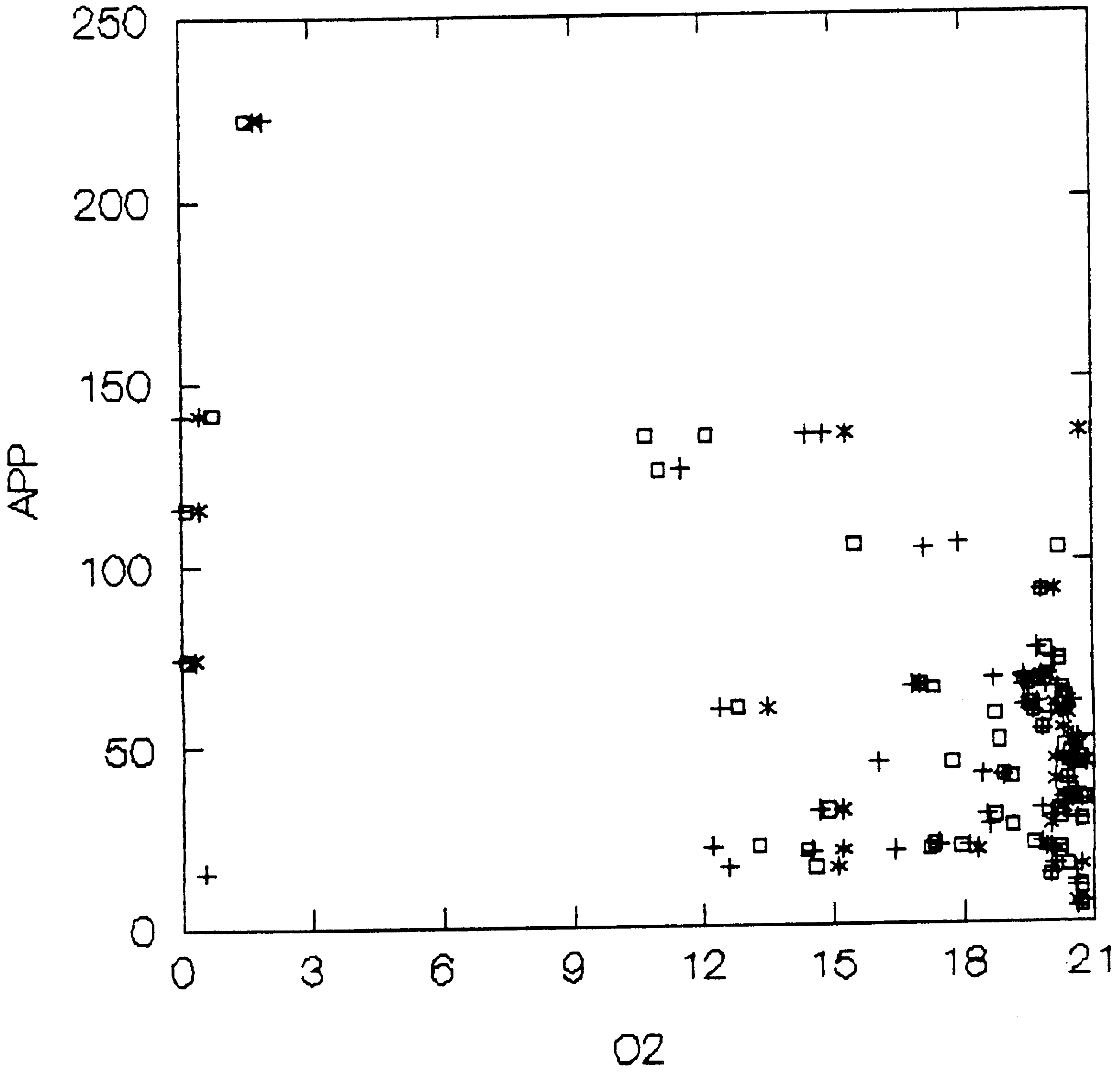
APP AND CO2 RELATION



PLUS SIGN - OCT.1989 SQARE - NOV.1989 STAR - FEB.1990

FIGURE 45

APP AND O2 RELATION



PLUS SIGN - OCT.1989 SQARE - NOV.1989 STAR - FEB.1990

Figures 44 and 45 show the relations between oxygen concentration, carbon dioxide concentration and APP. We expect some kind of correlation between APP and oxygen concentration as well as between APP and carbon dioxide concentration, but our monitoring data denied such correlations.

5.0 KINETIC TEST

Based on the acid-base accounting and the first two sets of monitoring results, four samples exhibiting extreme behaviors (the most acid generating and the most acid consuming) were submitted to Co^{3}stech Research Inc. in North Vancouver for kinetic (humidity cell) test. The test are yet to be completed. Table 4 presents the preliminary results from the initial ICP analysis and first two cycles (one cycle per week) of testwork.

Samples submitted for humidity cell tests were originally taken during drilling using a Becker Drill at 8 foot intervals. Whenever possible, as much as 5 kilograms of samples were taken. Otherwise all the cuttings from that interval were bagged. All samples were crushed, blended and split using a splitter to obtain sub-samples for acid-base accounting at BHP-Utah Mines Ltd, Island Copper Mine Environmental lab. The remainder of the samples were bagged again. Later.the sizes of all samples were reduced to approximately 1 kilograms by arbitrarily throwing away some samples from each bag. We selected some of these reduced samples and submitted them for humidity cell tests.

Table 5 is a list of the samples sumbitted for humidity cell tests along with their acid-base accounting results.

TABLE 5 INFORMATION OF SAMPLES SUBMITTED FOR HUMIDITY CELL TEST

Sample #	Sulphur (%)	APP (kgH2SO4/Tonne)	ACP (kgCaCO3/Tonne)
NWD#2 23'-31'	7.26	222.30	0.00
NWD#4 39'-47'	0.66	20.21	89.56
NWD#4 63'-71'	4.61	141.18	13.33
NWD#7 38'-47'	1.87	57.27	23.38
NWD#9 47'-55'	4.10	125.56	42.31

TABLE 4 HUMIDITY CELL TEST PRELIMINARY RESULTS

HEAD SAMHEAD SAMPLE ICP ANALYSIS

SAMPLE	Ag ppm	Al %	As ppm	B ppm	Ba ppm	Be ppm	Bi ppm	Ca %	Cd ppm	Co ppm	Cr ppm
NWD #2	< 0.2	3.05	95.0	< 10	30	14.0	< 2.0	1.01	25.0	24	64
NWD #4A	< 0.2	3.32	25.0	< 10	50	7.5	< 2.0	2.35	3.0	22	91
NWD #48	< 0.2	3.31	90.0	< 10	70	14.5	< 2.0	1.34	5.0	32	72
NWD #7	< 0.2	4.45	95.0	< 10	110	12.0	< 2.0	1.72	32.0	25	38
NWD #9	< 0.2	3.66	50.0	< 10	150	8.5	< 2.0	2.09	18.0	20	56

SAMPLE	Cu ppm	Fe %	K %	Li ppm	Mg %	Mn ppm	Mo ppm	Na %	Ni ppm	P ppm
NWD #2	532	9.75	0.08	18	1.77	6090	18	0.04	30	70
NWD #4A	517	5.88	0.08	15	2.19	2790	10	0.09	26	100
NWD #4B	1420	9.95	0.13	9	1.85	4480	26	0.12	27	90
NWD #7	311	8.95	0.08	21	2.02	6840	8	0.11	15	90
NWD #9	459	6.54	0.12	14	1.66	3840	< 1	0.13	14	110

SAMPLE	Pb ppm	Sb ppm	Sn ppm	Sr ppm	Th ppm	U ppm	V ppm	W ppm	Zn ppm	S (T) %
NWD #2	1020	< 5	40	< 1	88	< 10	107	70	>10000	4.5
NWD #4A	44	< 5	20	65	45	< 10	124	10	5070	0.7
NWD #4B	118	< 5	40	15	93	< 10	100	< 10	8270	0.7
NWD #7	336	< 5	20	37	73	< 10	116	90	>10000	2.4
NWD #9	356	< 5	20	146	53	< 10	748	60	>10000	3.0

LEACHIATE ANALYSIS

NWD #2

Cycle	Days	pH	Redox (mv)	Conduct. (mS/cm3)	Alkal. (mg/L CaCO3)	Acidity (pH4.5) mg/L CaCO3	Acidity (pH8.3) mg/L CaCO3	Cum. Acidity (pH8.3) (mg/L CaCO3)	Sulphate (mg/L)
1	7	3.65	377	4040	0	374.3	1674.5	534.2	3865
2	14	3.60	416	3820	0	158.4	1453.2	1032.6	3300

Cycle	Days	Cum.Sulphate) (mg/kg)	Fe++ (mg/L)	Fe+++ (mg/L)
1	7	1233.1	103.1	1.9
2	14	2364.9	63.1	0.5

Cycle	Days	As ppm	Ca %	Cd ppm	Cu ppm	Fe %	Mg %	Mn ppm	Mo ppm	Pb ppm	Zn ppm
1	7	1.50	521.0	3.15	10.70	100.0	191.00	89.20	0.79	1.00	463
2	14	1.15	400.0	3.50	7.50	63.6	220.00	98.00	0.88	1.65	552

NWD #4A

Cycle	Days	pH	Redox (mv)	Conduct. (mS/cm3)	Alkal. (mg/L CaCO3)	Acidity (pH4.5) mg/L CaCO3	Acidity (pH8.3) mg/L CaCO3	Cum. Acidity (pH8.3) (mg/L CaCO3)	Sulphate (mg/L)
1	7	7.45	247	1161	32.2	0.0	4.8	1.4	585
2	14	7.67	300	1404	40.5	0.0	3.6	2.7	650

Cycle	Days	Cum.Sulphate) (mg/kg)	Fe++ (mg/L)	Fe+++ (mg/L)
1	7	176.7	< 0.1	< 0.1
2	14	393.8	< 0.1	< 0.1

Cycle	Days	As ppm	Ca %	Cd ppm	Cu ppm	Fe %	Mg %	Mn ppm	Mo ppm	Pb ppm	Zn ppm
1	7	0.15	213.00	0.01	0.04	< 0.2	9.95	0.53	0.08	0.15	0.36
2	14	0.15	230.00	0.01	0.01	< 0.2	15.60	0.76	0.13	0.15	0.52

NWD #48

Cycle	Days	pH	Redox (mv)	Conduct. (mS/cm3)	Alkal. (mg/L CaCO3)	Acidity (pH4.5) mg/L CaCO3	Acidity (pH8.3) mg/L CaCO3	Cum. Acidity (pH8.3) (mg/L CaCO3)	Sulphate (mg/L)
1	7	4.35	371	2810	0.0	13.4	225.1	68.6	2165
2	14	4.44	416	3150	0.0	0.0	172.8	127.8	2305

Cycle	Days	Cum.Sulphate) (mg/kg)	Fe++ (mg/L)	Fe+++ (mg/L)
1	7	659.7	9.1	0.1
2	14	1449.5	3.6	< 0.1

Cycle	Days	As ppm	Ca %	Cd ppm	Cu ppm	Fe %	Mg %	Mn ppm	Mo ppm	Pb ppm	Zn ppm
1	7	0.60	451.00	0.45	10.70	9.2	178.00	84.10	0.21	0.75	66.20
2	14	0.70	386.00	0.66	6.50	3.6	330.00	150.00	0.25	0.30	96.20

NWD #7

Cycle	Days	pH	Redox (mv)	Conduct. (mS/cm3)	Alkal. (mg/L CaCO3)	Acidity (pH4.5) mg/L CaCO3	Acidity (pH8.3) mg/L CaCO3	Cum. Acidity (pH8.3) (mg/L CaCO3)	Sulphate (mg/L)
1	7	7.29	283	2030	48.8	0.0	5.8	1.9	1255
2	14	7.62	323	1139	25.3	0.0	6.7	4.0	540

Cycle	Days	Cum.Sulphate) (mg/kg)	Fe++ (mg/L)	Fe+++ (mg/L)
1	7	408.7	0.3	< 0.1
2	14	580.8	< 0.4	0.1

Cycle	Days	As ppm	Ca %	Cd ppm	Cu ppm	Fe %	Mg %	Mn ppm	Mo ppm	Pb ppm	Zn ppm
1	7	0.35	400.00	0.12	0.06	0.2	60.30	24.80	0.08	0.30	30.40
2	14	0.15	201.00	0.02	<0.01	<0.2	32.60	8.25	0.02	0.15	0.28

NWD #9

Cycle	Days	pH	Redox (mv)	Conduct. (mS/cm3)	Alkal. (mg/L CaCO3)	Acidity (pH4.5) mg/L CaCO3	Acidity (pH8.3) mg/L CaCO3	Cum. Acidity (pH8.3) (mg/L CaCO3)	Sulphate (mg/L)
1	7	6.76	131	2450	20.2	0.0	270.2	85.4	1855
2	14	6.66	384	1659	6.0	0.0	33.6	96.2	9610

Cycle	Days	Cum.Sulphate) (mg/kg)	Fe++ (mg/L)	Fe+++ (mg/L)
1	7	586.2	0.8	< 0.1
2	14	3367.2	0.2	< 0.1

Cycle	Days	As ppm	Ca %	Cd ppm	Cu ppm	Fe %	Mg %	Mn ppm	Mo ppm	Pb ppm	Zn ppm
1	7	0.55	545.00	0.82	0.71	1.8	75.20	46.60	0.37	0.80	216.00
2	14	0.25	361.00	0.15	<0.01	0.2	45.70	0.05	0.05	0.30	16.20

6.0 CLOSING REMARKS

A few parts of this report still involve theoretical speculations. Further studies are required to prove them. Monitoring results currently available are only those from October, 1989 to February, 1990. A full year of monitoring is required to reveal the influence of seasonal variations of temperature on the temperature profiles inside the dump.

REFERENCES

1. Golder Associated Ltd., January, 1989. Report to Environment Canada on the Drilling Program at the Mount Washington Mine Site, B.C.

2. Department of Mining and Mineral Process Engineering, the University of British Columbia. Acid Mine Drainage Study of the North Dump, A report prepared for BHP-Utah Mines Ltd., Island Copper Mine.

3. BHP-Utah Mines Ltd. and Rescan Environmental Services, April, 1988. Island Copper Mine South Wall Pushback - Description of Project and Related Environmental Issues, A report prepared for Vancouver Island Regional Reclamation Advisory Committee.

4. Sobek, A.A., W.A. Schuller, J.R. Freeman and R.M. Smith. 1978. Field and Laboratory Methods Applicable to Overburden and Minerals. U.S. Environmental Protection Agency Report 600/2-78-054

Appendix 3

BEACH DUMP DRILL HOLE
WATER QUALITY PROFILE
September, 1989

Hole #	Water Depth (m)	pH	Sulfate (ppm)	Alkalinity CaCO (mg/l)	Salinity %	Conduct. (umoh)	Diss. O	Dissolved Metals (ug/l)				
								Cd	Cu	Zn	Mn	Fe
1	Sur	7.18	980	2.94	8.49	11000	0.91	5.5	17	180	740	3.1
	5	7.40	1100	2.93	8.58	11000	0.45	5.4	11	130	760	2.3
	30	7.49	1600	3.43	17.53	20000	0.25	2.8	7.2	84	1000	160
	37						0.10					
2	Sur	7.25	2000	4.02	20.34	22000	1.56	8.1	17	510	71	4.3
	5	7.27	1900	3.91	20.50	23000	1.56	8.1	12	510	77	7.0
	30	7.27	2000	3.95	22.64	24000	0.50	5.3	21	380	300	5.8
3	Sur	7.33	2300	3.27	29.26	29000	0.30	1.4	5.6	110	840	100
	5	7.36	2300	3.29	29.37	28000	0.40	0.9	5.6	84	840	240
	20	7.31	2300	3.23	29.63	30000	0.30	0.8	3.2	79	810	260
	Bot	7.40	2300	3.27	29.37	30000	0.40	1.1	1.6	79	840	50
4	Sur	7.36	2300	3.62	25.64	27000	3.94	14	52	850	62	3.1
	5	7.47	2300	3.60	26.11	27000	0.71	9.9	44	640	120	1.2
	20	7.33	2300	3.46	26.94	27000	0.91	8.9	40	550	320	1.2
	Bot	7.51	2300	3.27	28.45	29000	0.30	4.5	32	320	610	2.3
5	Sur	7.59	2100	3.68	18.73	21000	2.32	16	41	700	50	2.3
	5	7.40	2200	3.40	22.01	23000	0.35	8.7	17	400	300	1.2
	20	7.41	2200	3.22	24.00	25000	0.40	6.9	15	260	490	7.8
	Bot	7.47	2300	3.13	24.89	26000	1.31	5.2	8	200	550	62

BEACH DUMP DRILL HOLE
WATER QUALITY PROFILE
September, 1989

								Dissolved Metals (ug/l)				
Hole #	Water Depth (m)	pH	Sulfate (ppm)	Alkalinity CaCO (mg/l)	Salinity %	Conduct. (umoh)	Diss. O	Cd	Cu	Zn	Mn	Fe
6	Sur	7.48	2100	3.35	23.93	25000	2.37	11	29	910	27	1
	5	7.54	2200	3.25	25.41	26000	0.61	7.7	22	700	120	1.2
	30	7.56	2300	3.02	27.98	28000	0.50	3.8	26	350	690	1.6
	40	7.50	2300	3.09	27.38	28000	0.81	3.4	15	370	680	9.4
7	Sur	7.54	2000	3.57	23.41	25000	3.43	11	84	730	38	1
	5	7.47	2200	3.52	23.67	25000	2.52	11	80	740	23	1
	30	7.49	2300	3.13	27.55	28000	1.06	3.8	37	300	590	12
	40	7.45	2300	3.12	27.48	28000	1.11	3.6	35	300	580	37
8	Sur	7.45	1400	4.04	9.83	12000	1.31	15	44	1300	42	1
	5	7.52	1400	3.78	11.00	13000	0.81	8.3	20	700	240	1
	20	7.70	1700	3.44	14.09	16000	0.61	5.6	21	420	840	1
	Bot	7.59	1700	3.44	14.48	17000	0.71	6.6	17	530	840	1
9	Sur	7.63	1800	3.76	14.83	17000	4.69	11	12	510	6.4	1
	5	7.55	1900	3.71	15.31	18000	3.63	8.8	12	440	11	1
	30	7.55	1900	3.44	18.55	21000	2.32	7.0	11	340	310	33
	Bot	7.54	1800	3.60	17.00	20000	1.72	7.7	7.2	350	260	67
10	Sur	7.57	2100	3.44	23.70	25000	1.62	7.5	64	570	54	1
	5	7.40	2300	3.38	24.73	26000	0.81	5.2	29	430	100	2.3
	30	7.52	2300	2.93	27.51	28000	0.45	2.1	21	170	450	490
	Bot	7.55	2300	2.92	27.31	29000	1.16	2.7	13	180	440	480

BEACH DUMP DRILL HOLE
WATER QUALITY PROFILE
October 26, 1989

								Dissolved Metals (ug/l)				
Hole #	Water Depth (m)	pH	Sulfate (ppm)	Alkalinity CaCO (mg/l)	Salinity %	Conduct. (umoh)	Diss. O	Cd	Cu	Zn	Mn	Fe
1	Sur	7.85	1000	3.60	5.43	7800	0.61	4.1	15	82	360	<0.9
	5	7.74	1000	3.64	5.54	8000	0.86	3.3	21	110	360	<0.9
	20	8.13	1100	3.62	5.56	7900	0.76	2.7	14	92	360	<0.9
	27	7.83	1100	3.63	5.90	8400	0.40	2.7	12	92	380	<0.9
2	Sur	7.65	2100	4.60	15.13	19000	3.45	13	26	900	16	<0.9
	5	7.73	2100	4.56	16.14	19000	2.93	11	21	770	10	<0.9
	20	7.67	2100	4.55	19.59	22000	1.80	7.2	20	490	51	<0.9
	31	7.82	2600	4.17	24.99	27000	0.53	2.7	22	220	1300	4.3
3	Sur	7.74	2400	4.60	23.70	27000	4.36	14	120	810	41	<0.9
	5	7.80	2600	4.40	26.54	29000	2.02	7.3	38	470	350	<0.9
	20	7.82	2600	4.11	26.99	30000	1.60	6.1	48	410	470	<0.9
	34	7.80	2600	4.11	27.83	30000	1.57	5.2	46	540	560	<0.9
4	Sur	7.78	2400	4.11	22.43	27000	3.90	16	100	950	11	<0.9
	5	7.87	2600	4.11	24.35	27000	1.01	11	61	750	12	<0.9
	20	7.80	2600	3.99	27.18	29000	0.61	6.2	38	380	470	62
	34	7.78	2600	3.77	26.51	29000	0.61	7.5	38	470	440	36
5	Sur	7.74	2400	4.14	15.94	19000	1.62	18	40	1000	170	<0.9
	5	7.74	2400	4.11	18.66	22000	0.41	15	37	820	52	<0.9
	20	7.96	2400	3.76	20.96	23000	0.52	11	24	510	320	<0.9
	38	7.89	2700	3.68	23.09	26000	0.42	7.1	16	350	520	130

BEACH DUMP DRILL HOLE
WATER QUALITY PROFILE
October 26, 1989

Hole #	Water Depth (m)	pH	Sulfate (ppm)	Alkalinity CaCO (mg/l)	Salinity %	Conduct. (umoh)	Diss. O	Dissolved Metals (ug/l)				
								Cd	Cu	Zn	Mn	Fe
6	Sur	7.84	2200	3.74	20.29	29000	2.57	9.1	34	770	10	<0.9
	5	7.85	2400	3.54	27.43	30000	0.52	3.1	10	230	940	160
	20	7.87	2800	3.52	27.62	29000	0.34	3.1	18	220	1000	130
	39	7.87	2700	3.23	28.36	31000	0.58	3.2	7.3	140	1000	150
7	Sur	7.82	2300	3.78	21.97	25000	2.00	10	100	660	37	<0.9
	5	7.76	2400	3.75	23.89	26000	0.53	6.1	54	500	140	1.3
	20	7.91	2600	3.70	25.12	27000	0.61	5.2	50	410	330	<0.9
	38	7.89	2600	3.64	26.54	28000	0.40	3.9	25	310	620	6.0
8	Sur	7.94	1500	3.61	6.79	9800	0.51	3.9	21	320	260	3.4
	5	8.14	1500	3.59	7.08	10000	0.49	2.9	11	210	310	<0.9
	20	7.85	1500	3.59	8.29	12000	0.85	2.3	11	170	620	<0.9
	27	8.02	1700	3.58	11.89	15000	0.50	2.1	6.9	150	840	17
9	Sur	7.87	2000	3.65	20.31	23000	0.40	6.2	9.2	290	490	240
	5	7.83	2000	3.68	20.40	23000	0.53	6.1	5.7	290	460	5.5
	20	8.00	2100	3.63	21.10	24000	0.39	4.1	8.4	190	580	250
	37	7.94	2000	3.64	20.78	24000	0.39	4.0	6.1	190	580	180
10	Sur	7.65	2100	5.22	14.12	18000	6.29	18	460	2400	2100	3.0
	5	7.85	2200	4.14	21.85	25000	0.68	5.7	110	630	330	1.7
	20	7.98	2300	3.65	25.41	28000	0.29	3.2	66	290	410	160
	38	8.00	2300	3.61	25.93	29000	0.61	2.2	25	25	440	260

BEACH DUMP DRILL HOLE
WATER QUALITY PROFILE
November 23, 1989

Hole #	Water Depth (m)	pH	Sulfate (ppm)	Alkalinity CaCO (mg/l)	Salinity %	Conduct. (umoh)	Diss. O	Dissolved Metals (ug/l)				
								Cd	Cu	Zn	Mn	Fe
1	Sur	7.70	750	3.29	<3.64	3500	2.04	1.2	18	85	15	<0.7
	5	7.70	750	3.13	<3.64	3600	1.43	4.2	6.1	65	41	0.7
	20	7.70	750	3.02	<3.64	3700	0.66	1.3	11	40	46	6.8
	26	7.70	900	3.09	<3.64	4600	0.71	0.5	9.7	50	92	14
2	Sur	7.38	1350	4.00	9.84	12000	2.91	5.3	18	550	18	0.7
	5	7.42	1300	3.92	9.84	13000	2.75	5.7	17	480	13	0.7
	20	7.44	1700	4.10	16.01	18000	0.46	5.2	13	340	41	1.4
	32	7.48	1800	3.91	19.01	21000	0.51	3.5	20	250	630	1.0
3	Sur	7.68	1850	4.38	19.18	21000	4.49	11	38	640	31	0.7
	5	7.33	2000	4.21	22.09	23000	0.51	7.1	38	440	99	1.0
	20	7.29	2000	3.95	23.55	26000	0.61	6.3	30	350	220	5.1
	33	7.40	2000	3.93	24.00	24000	1.02	5.3	28	330	270	2.0
4	Sur	7.40	2000	3.66	19.55	22000	1.77	12	53	750	48	0.7
	5	7.37	2000	3.75	20.97	22000	0.51	11	47	600	41	<0.7
	20	7.46	2200	3.48	25.06	27000	0.40	4.0	14	290	430	200
	33.5	7.37	2150	3.28	26.86	28000	0.35	3.5	13	260	620	570
5	Sur	7.37	1850	3.40	12.83	16000	5.45	11	24	770	120	0.7
	5	7.28	1900	3.49	14.87	17000	0.56	12	25	720	51	0.7
	20	7.29	2300	2.94	25.41	26000	0.35	2.2	4.6	150	700	650
	36	7.38	2300	2.92	25.41	26000	0.30	3.1	4.1	150	700	640

BEACH DUMP DRILL HOLE
WATER QUALITY PROFILE
November 23, 1989

Hole #	Water Depth (m)	pH	Sulfate (ppm)	Alkalinity CaCO (mg/l)	Salinity %	Conduct. (umoh)	Diss. O	Dissolved Metals (ug/l)				
								Cd	Cu	Zn	Mn	Fe
6	Sur	7.46	1800	3.34	17.97	20000	3.23	10	30	690	41	1.0
	5	7.51	2000	3.27	22.36	23000	0.51	4.5	17	410	390	12
	20	7.40	2300	3.07	26.53	27000	0.40	1.8	2.6	110	900	320
	38	7.64	2250	2.98	27.01	28000	0.66	1.5	1.5	100	590	320
7	Sur	7.42	2050	3.52	20.29	21000	2.63	9.0	51	530	130	0.7
	5	7.44	1900	3.49	20.96	23000	0.40	6.2	49	470	87	<0.7
	20	7.39	2150	3.20	25.24	27000	0.35	3.1	17	180	590	20
	38	7.51	2300	3.17	25.85	26000	0.46	2.6	11	80	690	190
8	Sur	7.80	1250	2.47	<3.64	3800	0.51	1.3	6.3	65	97	1.0
	5	7.77	1250	2.39	<3.64	3900	0.41	1.9	4.6	65	130	0.7
	20	7.82	1300	2.46	<3.64	4600	0.41	2.4	4.1	65	180	1.4
	27	7.72	1300	2.50	<3.64	5500	0.41	1.4	5.0	65	230	2.0
9	Sur	7.37	1700	4.00	12.08	12000	1.99	7.2	18	340	38	0.7
	5	7.43	1700	4.06	11.85	14000	1.84	5.4	10	360	43	<0.7
	20	7.43	1750	3.83	13.63	15000	0.51	4.9	7.4	280	170	1.0
	38	7.39	2100	3.10	23.09	20000	0.31	1.6	3.7	110	740	300
10	Sur	7.20	2000	3.88	16.86	18000	4.90	11	130	800	460	0.7
	5	7.55	2000	3.81	19.48	20000	0.91	5.9	55	500	130	0.7
	20	7.43	2050	3.63	21.26	23000	1.31	4.1	43	410	240	1.7
	38	7.44	2300	2.83	27.83	28000	0.46	2.4	7.6	110	500	530

BEACH DUMP DRILL HOLE
WATER QUALITY PROFILE
December 12, 1989

Hole #	Water Depth (m)	pH	Sulfate (ppm)	Alkalinity CaCO (mg/l)	Salinity %	Conduct. (umoh)	Diss. O	Dissolved Metals (ug/l)				
								Cd	Cu	Zn	Mn	Fe
1	Sur	6.76	600	3.20	<3.64	3300	2.04	1.2	23	100	18	2.5
	5	6.98	600	3.05	<3.64	3100	1.01	0.6	14	56	31	1.6
	20	7.08	600	2.99	<3.64	3200	0.72	0.6	11	45	25	1.6
	Bot	7.36	1400	3.47	13.02	13000	0.42	0.3	0.8	30	550	990
2	Sur	7.11	1400	3.92	9.61	9500	5.04	5.7	18	600	15	3.3
	5	7.17	1400	3.96	9.81	11000	4.43	5.0	15	560	9.2	2.9
	20	7.23	1600	4.07	13.47	14000	3.00	4.2	15	410	28	4.5
	Bot	7.28	1900	3.70	18.83	18000	1.56	3.1	21	280	560	5.4
3	Sur	7.56	1800	4.55	17.83	17000	4.89	7.2	59	640	15	3.3
	5	7.47	2000	4.34	19.69	18000	3.23	7.1	32	500	51	1.6
	20	7.56	2100	3.38	23.67	21000	1.41	4.0	24	280	270	2.1
	Bot	7.54	2100	3.70	24.52	22000	0.93	3.8	7.8	200	320	21
4	Sur	7.54	2100	3.85	18.08	17000	5.49	13	53	950	19	1.2
	5	7.52	2200	3.77	19.78	18000	2.07	8.1	46	580	5.3	1.6
	20	7.58	2300	3.60	23.76	21000	1.42	6.4	19	300	320	71
	Bot	7.50	2300	3.46	25.15	22000	1.03	4.0	17	270	420	240
5	Sur	7.52	2100	3.53	14.76	14000	2.52	9.1	22	640	27	1.6
	5	7.47	2100	3.42	16.07	15000	1.21	11	22	640	16	2.5
	20	7.54	2200	3.36	17.05	16000	1.16	9.9	21	580	85	26
	Bot	7.47	2100	3.30	18.64	17000	0.81	8.7	18	480	200	61

BEACH DUMP DRILL HOLE
WATER QUALITY PROFILE
December 12, 1989

								Dissolved Metals (ug/l)				
Hole #	Water Depth (m)	pH	Sulfate (ppm)	Alkalinity CaCO (mg/l)	Salinity %	Conduct. (umoh)	Diss. O	Cd	Cu	Zn	Mn	Fe
6	Sur	7.69	1800	3.43	18.36	17000	4.58	5.7	30	640	13	1.6
	5	7.61	1900	3.37	20.10	18000	1.91	5.8	25	550	70	3.3
	20	7.67	2300	3.21	24.14	21000	0.55	2.3	7.3	170	560	110
	Bot	7.60	2100	3.19	24.10	22000	0.55	2.0	5.6	180	460	110
7	Sur	7.58	2000	3.67	18.48	17000	5.03	5.2	59	550	95	33
	5	7.56	2100	3.51	20.59	19000	0.70	5.0	50	460	27	1.6
	20	7.56	2100	3.46	27.71	20000	0.81	4.3	37	370	170	2.1
	Bot	7.58	2100	3.37	23.13	21000	0.70	3.5	23	290	300	5.4
8	Sur	7.89	1100	2.78	<3.64	2500	6.07	6.6	30	810	48	2.1
	5	7.67	1000	2.72	<3.64	1700	3.12	2.3	14	340	33	1.6
	20	7.95	1400	2.69	6.50	7500	0.50	1.1	7.3	120	350	3.7
	Bot	7.83	1200	2.68	4.98	6400	0.60	1.2	7.8	170	250	3.3
9	Sur	7.63	1700	3.82	13.47	14000	0.58	3.1	8.4	180	200	20
	5	7.69	1700	3.79	13.47	14000	0.66	2.3	7.8	180	210	4.9
	20	7.52	1700	3.67	15.25	15000	0.60	2.3	7.3	170	220	42
	Bot	7.74	1800	3.55	16.47	16000	0.40	1.8	5.9	110	340	100
10	Sur	7.60	2000	4.06	16.38	16000	6.35	9.5	150	800	260	2.1
	5	7.59	2000	3.93	18.23	18000	1.41	6.5	79	550	110	3.4
	20	7.58	2200	3.31	23.55	22000	0.55	1.7	15	200	300	190
	Bot	7.61	2200	3.34	23.51	23000	0.48	1.6	11	190	270	170

BEACH DUMP DRILL HOLE
WATER QUALITY PROFILE
January 24, 1990

Hole #	Water Depth (m)	pH	Sulfate (ppm)	Alkalinity CaCO (mg/l)	Salinity %	Conduct. (umoh)	Diss. O	Dissolved Metals (ug/l)				
								Cd	Cu	Zn	Mn	Fe
1	Sur	7.33	650	166.5	<3.64	3100	1.71	1.6	39	210	6.7	1.0
	5	7.46	650	155.5	<3.64	3200	1.00	1.0	22	110	20	<1
	20	7.65	700	150.3	<3.64	5500	0.50	0.8	13	58	68	1.0
	26	7.59	950	3.44	9.75	12000	0.20	1.2	1.8	61	490	830
2	Sur	7.59	900	4.12	8.65	12000	3.36	4.1	14	390	13	1.9
	5	7.53	1050	4.36	11.87	15000	0.80	3.3	11	260	9.5	1.9
	20	7.55	1200	4.21	15.63	19000	0.30	2.2	12	210	190	5.3
	31	7.55	1300	4.09	16.70	20000	0.50	2.7	19	200	330	2.4
3	Sur	7.53	1300	4.52	16.68	20000	4.51	7.1	60	550	15	<1
	5	7.57	1350	4.29	19.57	24000	0.80	6.3	29	400	20	<1
	20	7.61	1550	3.77	23.76	28000	0.65	3.1	18	190	250	8.7
	33	7.77	1600	3.61	24.99	30000	1.71	2.2	5.7	120	330	5.3
4	Sur	7.60	1400	3.93	17.72	23000	1.50	10	49	620	8.3	1.0
	5	7.61	1450	3.93	18.97	24000	0.50	8.4	46	560	5.3	1.9
	20	7.59	1600	3.66	23.79	28000	0.40	2.9	9.6	190	420	230
	33	7.75	1800	3.61	23.96	28000	0.50	4.5	14	230	460	370
5	Sur	7.70	1900	3.48	12.46	17000	4.30	13	22	730	53	<1
	5	7.57	1900	3.69	13.29	18000	0.70	11	27	630	9.5	1.9
	20	7.59	2100	3.34	20.04	25000	0.40	5.9	11	280	390	280
	36	7.62	2100	3.28	22.27	26000	0.40	4.8	7	190	500	400

BEACH DUMP DRILL HOLE
WATER QUALITY PROFILE
January 24, 1990

								Dissolved Metals (ug/l)				
Hole #	Water Depth (m)	pH	Sulfate (ppm)	Alkalinity CaCO (mg/l)	Salinity %	Conduct. (umoh)	Diss. O	Cd	Cu	Zn	Mn	Fe
6	Sur	7.75	1650	3.61	16.16	21000	4.45	7.7	30	650	23	1.0
	5	7.72	1900	3.48	20.68	24000	0.70	4.5	19	430	220	9.6
	20	7.74	2100	3.28	23.91	28000	0.85	2.1	8.7	180	710	220
	37	7.70	2300	3.10	25.78	30000	0.30	1.0	3.9	91	760	340
7	Sur	7.99	1800	3.89	16.63	21000	3.20	6.7	53	510	11	1.9
	5	7.71	1900	3.75	18.99	24000	0.80	5.3	46	400	62	1.0
	20	7.70	2100	3.48	22.67	26000	0.65	2.8	21	210	420	6.7
	38	7.73	2100	3.41	26.75	27000	0.50	3.0	14	180	510	58
8	Sur	7.86	900	124.3	<3.64	2600	0.50	1.1	7.5	120	63	<1
	5	8.01	900	119	<3.64	2600	0.80	0.8	4.4	81	97	<1
	20	7.86	1050	125	<3.64	4900	0.55	0.7	4.8	71	220	1.4
	27	7.88	1200	2.62	5.11	6800	0.70	0.6	4.4	71	380	2.9
9	Sur	7.73	1400	4.30	7.17	9200	3.51	2.5	13	160	10	<1
	5	7.92	1400	4.30	7.36	9400	3.41	2.6	9.6	160	10	<1
	20	7.73	1400	4.16	8.67	10000	2.31	2.5	6.1	150	68	1.0
	38	7.81	1500	4.09	9.58	12000	2.46	2.6	6.1	140	110	1.9
10	Sur	7.54	1800	4.05	16.21	18000	2.56	6.7	130	540	58	<1
	5	7.66	1900	3.98	18.27	19000	0.50	4.5	53	400	61	2.4
	20	7.77	2100	3.71	20.48	22000	0.75	2.8	28	260	190	3.4
	39	7.67	2300	3.06	25.62	26000	0.30	1.3	9.6	91	420	510